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by

Marion Annie Marshall Wilson, B.Sc.,

Physical Laboratory,

University of Edinburgh.

<u>TITLE</u>

Investigations on the Scattering of X-Rays.

1939?

INTRODUCTION

Many workers[1] in this laboratory have found that when using heterogeneous beams of X-rays the results they obtained were not those anticipated from a knowledge of the behaviour of homogeneous beams. The experiments described in this work consist of scattering a heterogeneous beam of X-rays from some material of low atomic number, and comparing the portion of the beam scattered at 90° to the primary beam with the primary beam itself under given conditions. These conditions are so chosen that the secondary beam does not contain any characteristic radiation from the atoms of the scatterer.

We shall first consider the case in which the primary radiation is homogeneous, and discuss the results expected from such experiments. When these scattered rays in any one direction are examined in an X-ray spectrometer it is known that the beam now contains two wavelengths, one the original wavelength and the other somewhat longer. The increase in wavelength depends only on the angle between the primary and secondary beams. This is the well-known Compton[2] effect.

The presence in the scattered beam of radiation of the same wavelength as the primary has been explained by the classical theory. The quantitative development of the quantum theory gives that the increase of wavelength on scattering is for free electrons

$$d\lambda = \frac{h}{m.c.}(1 - \cos\phi)$$

where h is Planck's constant, m the mass of the electron, c the velocity /

[1] See pg. 8

velocity of electro-magnetic radiation and ϕ the angle between the direction of the primary and scattered rays. This result has been verified by Schrodinger[3] from the standpoint of wave-mechanics.

Since the secondary beam is of longer wavelength than the primary it must be more easily absorbed. This holds whether the primary beam contains radiation of one or more wavelengths. This expected increase of absorption coefficient has not always been recorded by workers in this laboratory. On many occasions absolute equality of absorption of the beams has been found. At other times, equality has been present over a limited range, until at some definite point the increase of absorption coefficient reveals itself absuptly. And yet many results are precisely those expected from the Quantum Theory. Another feature of their work has been the sudden change in the type of result obtained. An experiment which one day showed the beams to be equally absorbed, has on the next given the quantum result without any alteration being made in the conditions of the experiment.

The work undertaken by the writer was designed to investigate these points. The experiments were of two types (a) Filtering Experiments, (b) Scattering Experiments. We shall begin by considering the former.

In the Filtering or Progressive Absorption experiment a comparison is made between the primary beam of X-rays and that scattered at 90°, when both are filtered by equal amounts of aluminium or other filtering materials. The scatterer is set at /
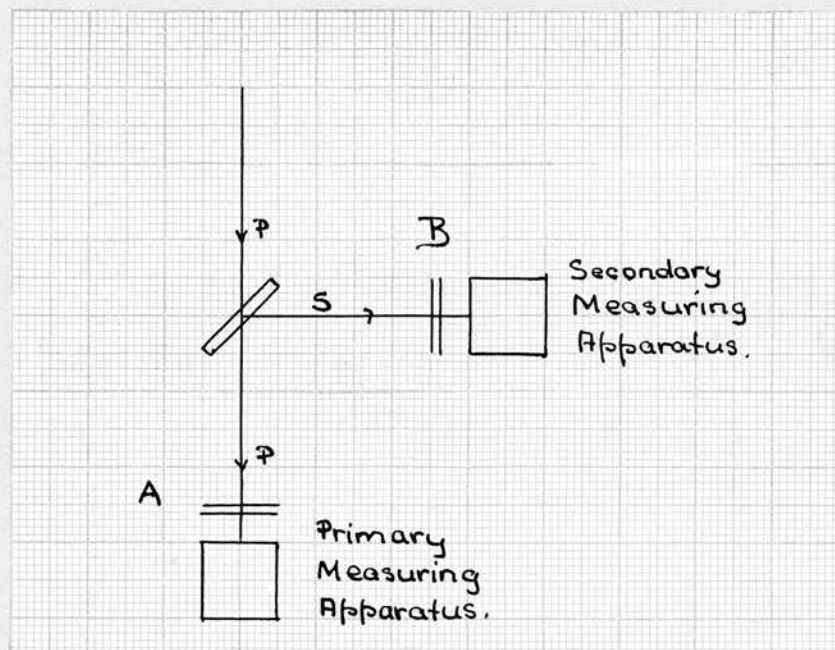
Figure 1

at 45° to the primary beam.   This arrangement ensures that both
beams pass through equal thicknesses of the scatterer.   Filters
may be inserted in the beams at A and B.   The rays enter the
measuring apparatus after passing through the filters.   As the
thickness x , of the filters is increased we obtain for each
value of x the ratio: Ionisation produced by the secondary
beam/Ionization produced by the primary beam,   thus determining
how this ratio varies with x .   According to the classical
theory this ratio is independent of x , but on the quantum theory
this relationship does not hold.

If we consider a homogeneous primary beam scattered as
described above, and let

  S be the intensity of the secondary beam after filtering,

  S' be the intensity of the secondary beam before filtering,

  μ_s be the absorption coefficient of the secondary radiation in
                                                  aluminium,

  x be the thickness of filtering aluminium.

Then /

Then

$$S = S' e^{-\mu_s x.}$$

Similarly

$$P = P' e^{-\mu_P x}$$

and

$$S/P = (S'/P') e^{-(\mu_s - \mu_P) x}$$

$$= C e^{-y x x}$$

(4)

since $\mu_s > \mu_P$, y is positive. Therefore, since the ionization is nearly related to the intensity of X-rays producing it, we conclude that the quantum theory predicts that S/P decreases exponentially as x increases.

It is difficult to extend the above discussion to the case of the heterogeneous primary radiation, which is that actually employed, as the fraction of radiation scattered varies with wavelength; but each constituent of the primary beam must give rise to one of longer wavelength in the secondary. Owing to the softer nature of the secondary the ratio: Ionization in the secondary electroscope/Ionization in the primary electroscope (which will subsequently be referred to as S/P) must decrease with increasing x . The greatest rate of decrease of S/P must occur for the first filtering sheets as these absorb the softest radiation very strongly, making the beam as a whole more penetrating. Thus we are led to expect for the shape of the curve of S/P plotted against x one which decreases with increasing x , showing the greatest rate of decrease for small values of x . The precise shape of the curve must depend on the energy wavelength distribution of the primary beam, as different wavelengths are scattered in different proportions.

The performance of this experiment has produced very interesting results which are described on pages 29-47

The /

The Scattering Experiment consists of determining how the ratio S/P varies as the voltage on the tube is altered. This of course alters the wavelength of the X-rays. Using classical ideas J. J. Thomson,[4] assuming the primary beam to be unpolarised and of intensity I_0 , calculated the intensity S_ϕ of the beam scattered by a single electron in a direction making an angle with the forward direction of the primary beam to be

$$S_\phi = I_0 (1 + \cos^2 \phi)(e^4/2r^2m^2c^4) = x \qquad [1(a)]$$

where e is the charge on an electron in e.s. units, m is the electronic mass and c the velocity of the radiation, r is the distance from the scattering electron to the point where I_ϕ is measured. Since in the experiments under consideration $\phi = 90°$

$$S_{90}/I_0 = S/P = e^4/2r^2m^2c^4 = \text{constant}. \qquad (2)$$

Thus in the scattering experiment the graph of S/P against λ would be a straight line parallel to the λ axis. This result is independent of whether or not the primary radiation is homogeneous, as Thomson's formula is not based on any special assumption as to the form of the electromagnetic pulse. The scattering coefficient, i.e. the fraction of incident X-rays scattered per cm. of the material traversed, can also be calculated. This is found to be constant for various wavelengths. The mass-scattering coefficient, i.e. the fraction scattered per unit mass of scattering material per unit cross-section of the beam, is a quantity in more frequent use. It is also, on this theory, a constant for varying λ for any given scatterer.

Let us now consider the application of the quantum theory to the scattering experiment, assuming that the primary beam is homogeneous /

homogeneous. Thomson's equation must be corrected for quantum scattering and some assumptions must be made in so doing. The precise nature of these assumptions influences the exact form of the formula.

An equation was derived by Breit[5] and has since been confirmed by various types of quantum mechanical calculations by Dirac[6] and Schrodinger. It is usually referred to as the Breit-Dirac formula and may be given as

$$\overline{I}_\phi / \overline{I}_0 = (1 + \alpha \operatorname{vers} \phi)^{-3} = \left(\frac{\nu'}{\nu}\right)^3 \tag{3}$$

where ν' is the frequency of the secondary beam and ν that of the primary, $\left(\alpha = \frac{h\nu}{mc^2}\right)$. and $I_0 = \infty$ in $[1\omega]$

A somewhat more exact form has been obtained by Klein and Nishina[7] using the Dirac quantum mechanics which are invariant to Lorentz transformations. For the normal X-ray region these formula may be equated.

Therefore, in order to predict the shape of the scattering curve for a homogeneous primary, it is only necessary to calculate the wavelength of the X-rays produced by a tube for a given voltage and, since the change of wavelength at scattering at right angles is known, the wavelength of the secondary beam is known. As the wavelength of the primary is increased it is easily seen that $\overline{I}_\phi / \overline{I}_0$ increases. This relationship must be corrected for the different ionizations produced by different wavelengths before any conclusions can be drawn as to the shape of the S/P curve.

The ionization produced in any gas by an X-ray beam of given intensity is very nearly proportional to its absorption coefficient /

(8)

coefficient in the gas. Experiment shows that the absorption
coefficient of X-radiation is proportional to the cube of its
wavelength. (There is some divergence of opinion as to the
precise value of this index. The value 3 is the most probable.)
Thus for equal intensities of secondary and primary beams we have
the ratio of the ionizations produced in the respective chambers

$$S/P = \mu_s/\mu_P = \left(\frac{\lambda'}{\lambda}\right)^3 \tag{4}$$

But equation (3) gives us the actual ratio of the intensities
of the secondary and primary beams in the scattering experiment,
therefore the ratio of ionizations produced in the chambers is
given by

$$S/P = \left(\frac{y'}{y}\right)^3 \left(\frac{\lambda'}{\lambda}\right)^3 = \text{constant}$$
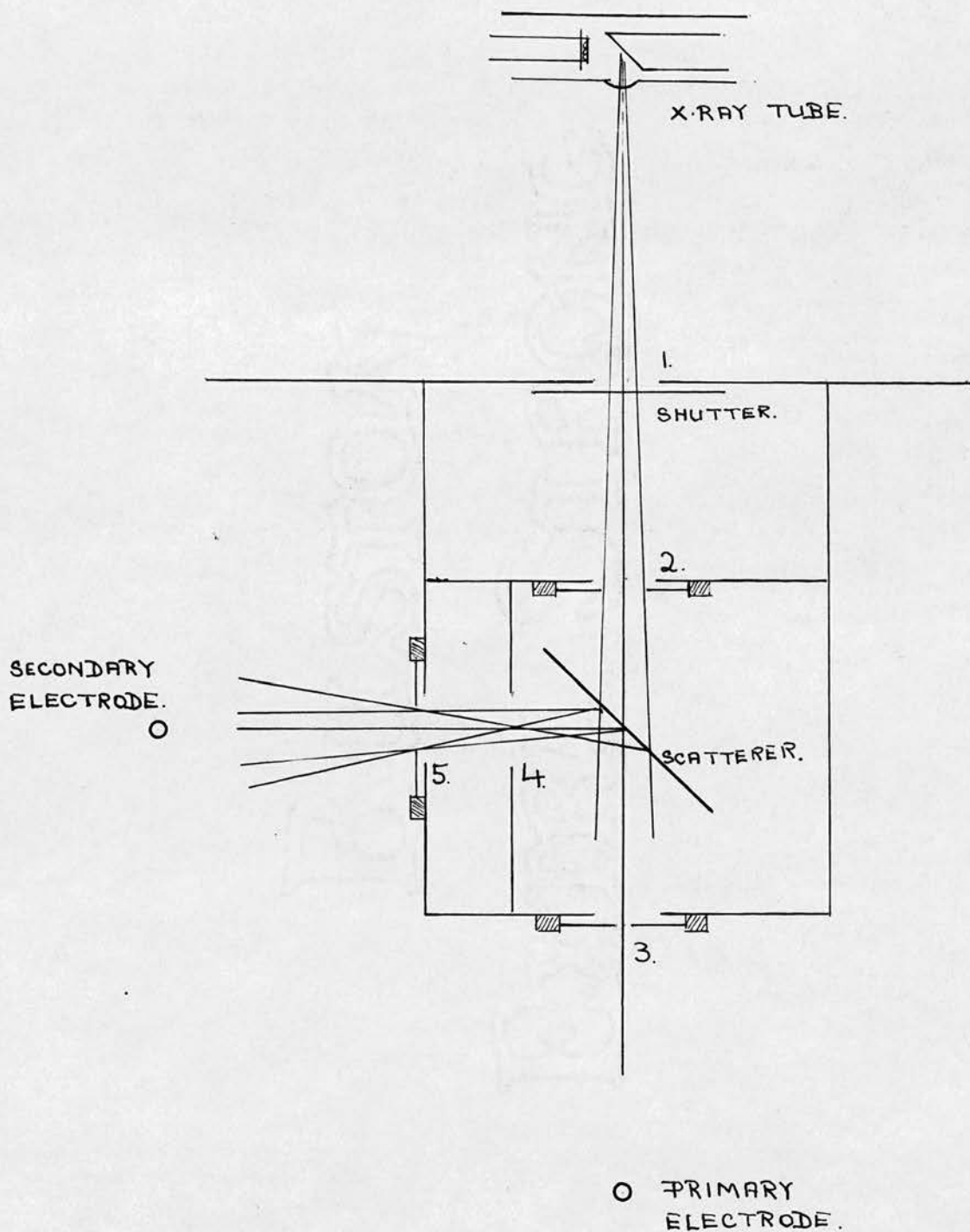
The extension of these arguments to the case of a hetero-
geneous primary introduces many complications. The ionization
in either electroscope is the sum of the ionizations produced by
each component. The intensity of each separate wavelength in
the 'white' radiation of the tube, its scattering coefficient,
its wavelength on scattering must all be known. The resultant
expressions for P and S must be summed over the available range.
The expression thus obtained for S/P must next be corrected for
absorption in the scatterer, for polarization and for any stray
effects. It is obvious that the complete mathematical treat-
ment is impossible unless the X-radiation is examined by an X-ray
spectroscope. Even with such examination the calculation is a
very complicated one. The extreme simplicity of the experimental
results (see pp. 48-56) is in striking contrast to the elabora-
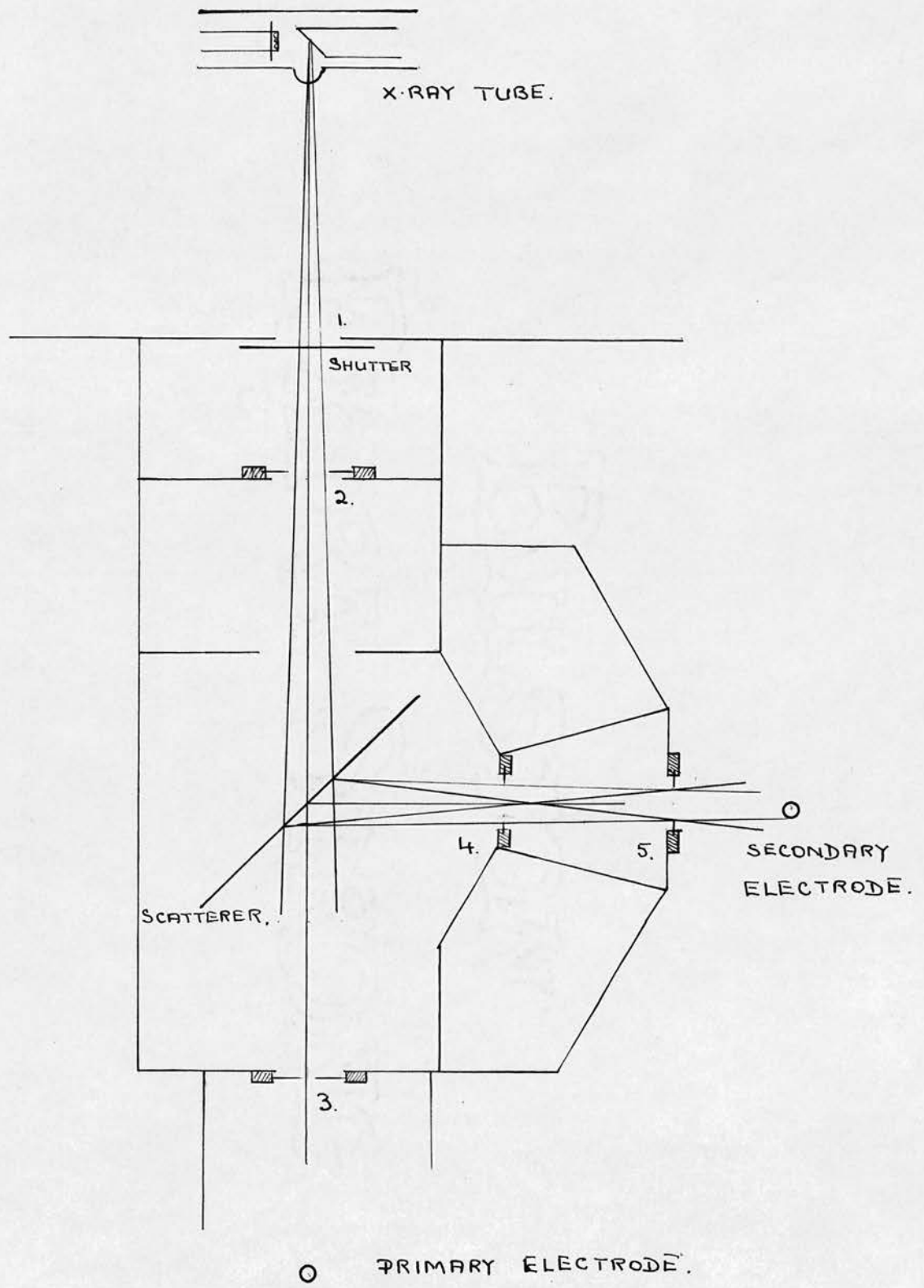tion of the mathematical formulae.

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PLAN of APPARATUS I.
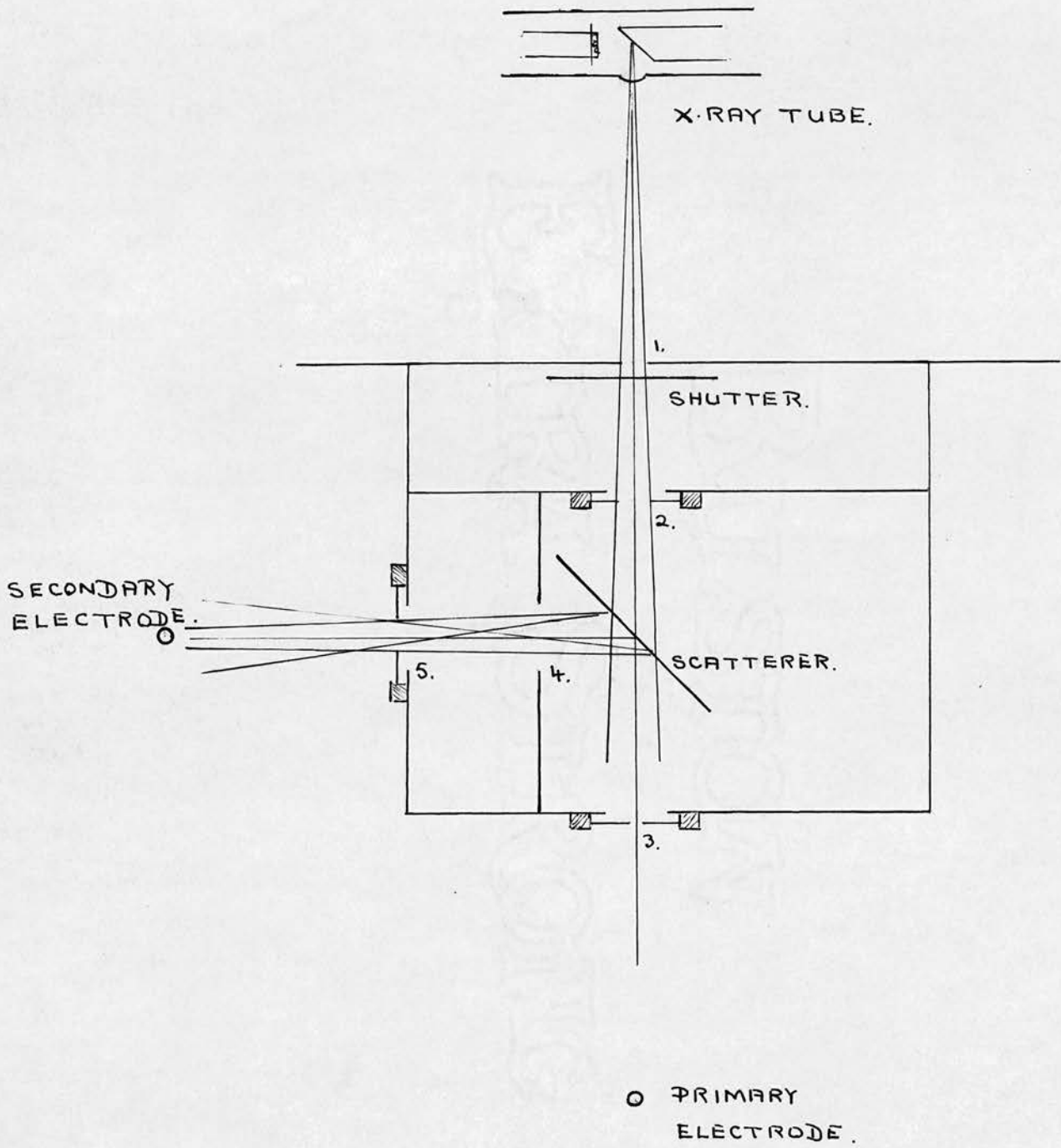

X·RAY TUBE.

1.

SHUTTER.

2.

SECONDARY
ELECTRODE.
O

SCATTERER.

5.   4.

3.

O   PRIMARY
ELECTRODE.

SCALE: 1/5 FULL SIZE.

PLAN OF APPARATUS II.

X·RAY TUBE.

1.

SHUTTER

2.

3.

4.   5.

SCATTERER.

SECONDARY
ELECTRODE.

O   PRIMARY ELECTRODE.

SCALE : 1/5 FULL SIZE.

PLAN OF APPARATUS III.

X·RAY TUBE.

1.

SHUTTER.

2.

SECONDARY
ELECTRODE.
O

5.   4.   SCATTERER.

3.

O PRIMARY
   ELECTRODE.

APPARATUS AND TECHNIQUE

As it is very important to discover which (if any) of the experimental results are influenced by the arrangement of the apparatus, three separate sets of apparatus with different arrangements have been used in the course of the experiments described in this work. The details of these may be seen in the accompanying plans. While these were slightly different the main features of each were the same. Briefly, they were these: The X-Ray tube, excited by some high tension source, was enclosed in a lead box. A narrow beam of X-Rays was allowed to pass through apertures 1 and 2 and to fall on the scatterer. This usually consisted of a slab of paraffin wax or a number of sheets of filter paper. These substances were chosen as they consist entirely of light atoms which emit only scattered and not characteristic radiation at the voltages under consideration. This scatterer was set so that scattered rays from it entering the secondary measuring apparatus passed through the same thickness of wax as the primary. This was the case when the scatterer was set at an angle of $45°$ with the primary, and was true for radiation scattered at any point in the scatterer. Of course, if the secondary was much softer than the primary, and the slab of wax was thick then equal thicknesses of wax filtered the secondary more than the primary. The slab was set so that it was the radiation from the back face which entered the secondary chamber.

After penetrating the scatterer the primary radiation then passed /

passed through aperture 3. This could considt of one or more
holes, but was always very small owing to the great intensity
of the primary radiation. The ionisation chamber, which was
connected to the primary electroscope, then received the radiation
which had passed through aperture 3.

These apertures 2 and 3 could be altered since lead slides
with holes of varying size could be inserted there. Aperture 1
was not in general altered in the course of the experiments.
On apparatus I it was 1.6 cm.; on apparatus II, 3.0 cm. and on
apparatus III, 1.0 cm. By altering aperture 2 the cone of
radiation from the tube could be altered in solid angle.
When aperture 2 was fully open the angular spread of the beam in
the plane of the diagram was never more than 8° or 10° and
usually considerably less. Apertures 4 and 5 permitted the
scattered rays to enter the secondary ionisation chamber.
Owing to the smaller intensity of the secondary beam these
apertures were wider than aperture 3. Usually the diameter
of these apertures was of the order of ten times the diameter
of aperture 3. Unfortunately this resulted in the inclusion
in the secondary beam of rays scattered at angles of $85^{\circ} - 95^{\circ}$
with the primary which is rather a large departure from the ideal
of measuring rays scattered at 90°. The influence these oblique
rays may be expected to have will be discussed later (page 108).
The lead forming the screens and divisions in the apparatus was
in all cases 3 mm. in thickness which is fully adequate to
prevent /

prevent the penetration of X-rays of the wavelength employed.

The method of measuring X-ray intensity was in all cases by ionisation. This has one great disadvantage. Equal intensities of X-rays of different wavelengths have different ionising powers per cm. As the X-rays under investigation had very varied wavelengths this had always to be taken into account. This point is developed elsewhere.

The chambers consisted of circular brass cylinders covered with 3 mm. lead to prevent any action of stray radiation. The dimensions of these were identical for apparatus I and III - diameter of cylinder = 10 cm., length of cylinder = 5 cm. For apparatus II, the dimensions are diameter = 14.5 cm. and length = 10 cm. One end of the cylinder was covered with an aluminium window 0.01 cm. thick through which the radiation entered the chamber. Care was taken that the spread of the beam when it reached the window was so small that all rays entered through its central part. The chamber was lined with aluminium 0.01 cm. in thickness and several thicknesses of filter paper. Inlet and outlet tubes permitted of the use of any special gas to fill the chamber.

Figure 2 will make the electrode arrangements clear. The electrode itself consisted of an aluminium ring whose diameter was about 2 cm. less than that of the cylinder. Fine cotton veiling was stretched across it. As this was not a very good conductor, especially after long exposure to SO_2, the cotton was /

Ebonite Plug.

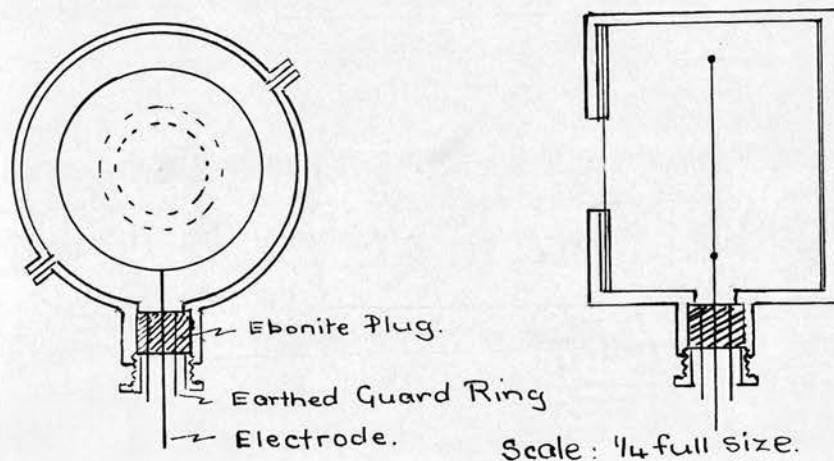Earthed Guard Ring

Electrode.

Scale: ¼ full size.

Figure 2.

was painted with indian ink. It is essential that all metal parts should be outside the direct X-ray beam, otherwise the X-rays would produce secondary rays from them. A metal connecting rod passed through an ebonite plug to the electroscope.

In order that the measurements of secondary and primary instruments may be comparable the two ionization chambers on any one apparatus must be identical in construction and contain gases identical in composition. The chambers then absorb equal proportions of the incident beams, assuming that these are of similar constitution. The gases used were SO_2 or air, both at atmospheric pressure. These were used as over the wavelength range of X-rays employed there are no critical absorption wavelengths for these gases. These ionization chambers were
                on
held insulating supports and could have a potential applied to them.

It /

It was, of course, necessary to make quite certain that
the currents in the chambers were the saturation currents, i.e.
to ensure that all the ions produced were collected by the
electrode before recombination could take place. The way in
which this was frequently tested was to reduce the intensity
of radiation very considerably and to see whether the relative
values of secondary and primary ionization had altered.
Another way of testing was to alter the values of the potentials
applied to chamber and electroscope and to measure the resulting
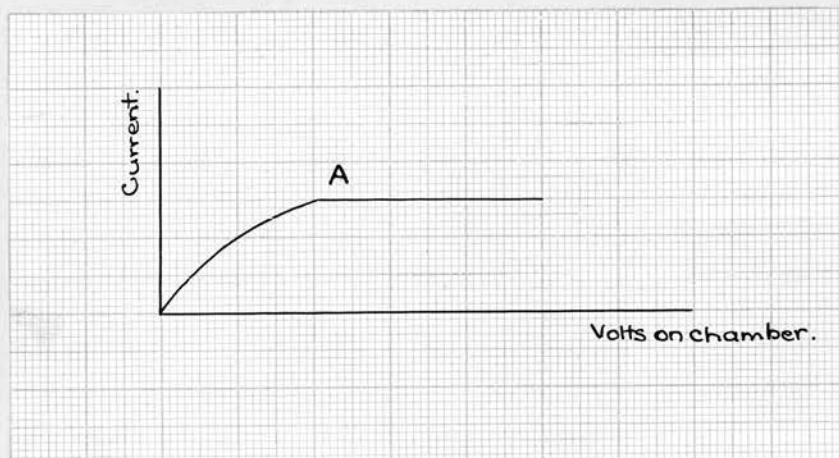ionization currents. If it was found that the values for the

Figure 3.

system gave a point on the curve to the right of A saturation
was ensured. In all cases it was found that the values of
potential applied were amply more than sufficient to produce
saturation.

The primary ionization current was always measured by the
simple cubical gold leaf air electroscope, as the intensity of
the primary was such that no great sensitivity was needed to
measure it. On apparatus II (in which the primary ionization
chamber /

chamber was charged to 180 volts negative) the electrode of
the electroscope was charged to 180 volts positive.   On
apparatus I and III (where the chambers were earthed) the
electrode was in each case charged to 240 volts positive.   The
movement of the gold leaf was measured by a suitably placed
low-power microscope with graduated eye-piece.

For some of the early experiments on apparatus I the
secondary electroscope was precisely the same as the primary.
This was not very satisfactory as the intensity of the secondary
was very small compared with that of the primary.   In order to
have deflections in the two electroscopes comparable in size
(to reduce errors in the ratio) it was necessary to open the
secondary apertures (4 and 5) very widely.   This meant that
the scattering angle of rays entering the chamber varied from
80° to 100° (approx.).   Therefore this cubical electroscope for
the secondary was replaced by a much more sensitive one of the
type described by C. T. R. Wilson.   The electrode and hence the
leaf was initially at earth potential.   The plate was maintained
at a negative potential of 200 volts.   The deflection of the
leaf was also read by a microscope with graduated eye-piece.
The sensitivity could be most easily altered by altering the
potential on the plate.   This is the method used in practice.
A slow motion screw attached to the plate made an adjustment
of its position and, therefore, the sensitivity possible.
The case of the instrument was earthed.   On apparatus III the
secondary ionization was also measured by an instrument of this
type /

type.

On apparatus II the secondary ionization was measured by
an electroscope with two tilted plates of the Bumstead[1] type.
The two plates were charged to equal and opposite potentials
usually 180 volts.

As the determination of the ratio of ionizations, i.e.
deflections of the secondary and primary electroscopes was the
object in view, one of these was taken as standard and the
variation of the other with regard to it was measured.   In the
case of apparatus II the primary deflection was taken as
standard.   During any one experiment the standard deflection
was always taken over precisely the same part of the scale.
This was usually of the order of 12 divisions.   As coincidence
between the division mark and the leaf edge could be judged
very accurately, this deflection was made from one division
mark to another.   Thus fractions of a division did not have to
be estimated.   The error in the determination of primary
deflection (P) must be very small.   It was only in the deter-
mination of secondary deflection (S) that fractions of a
division had to be estimated.   It was found that deflections of
the secondary were linear as compared with the primary as long
as the secondary deflection did not exceed about 15 divisions
from the zero position, for as the leaf passed that point it
was seen to accelerate very slightly and in fact to lose
stability.   The readings were, therefore, kept smaller than
this.   The determination of this ratio S/P was repeated three
or /

or four times under identical conditions and the average taken, before the value was determined for another point.

For apparatus I and III it was found that over no range are the deflections in the secondary linear. Therefore, one fixed deflection of the secondary was taken as standard in the method described above, while variations in P were noted and the ratio S/P obtained as above. This method was employed on apparatus II. The results obtained on it were independent of which electroscope was taken as the standard.

The cubic electroscopes were covered with lead for protection. The case was earthed and lined in the same way as the chambers, i.e. with Al and filter paper.

Since the rate of deflection of the leaf was measured care was taken to keep electrical leaks small. The number of divisions through which the leaf leaks in one hour was frequently measured. This was done both when the tube was running and when it was not. In every case these deflections were less than one division in one hour. As the readings were of the order of 20 divisions in 4 minutes the correction is seen to be of the order of about 1 in 250. Now in certain experiments with low intensities the readings were longer than this, but these were taken at times when the leaks were very small. Corrections were applied to these readings but in all results included in this work the corrections were much smaller than the observational error.

The most important precaution was to ensure that the sensitivity /

sensitivity of either electroscope did not change throughout the experiment.   To measure the sensitivity of the secondary electroscope a standard cell was connected directly to it and the deflection measured.   The sensitivity of the cubic electroscope did not alter very appreciably and may be left out of consideration.   On several occasions when the sensitivity did alter the readings were corrected for this, but in general if conditions were not sufficiently steady to allow repetition of readings (within experimental error) no results were recorded.

Two different types of high tension source were used in these experiments:

      (a) Alternating Potential,

      (b) Direct Potential.

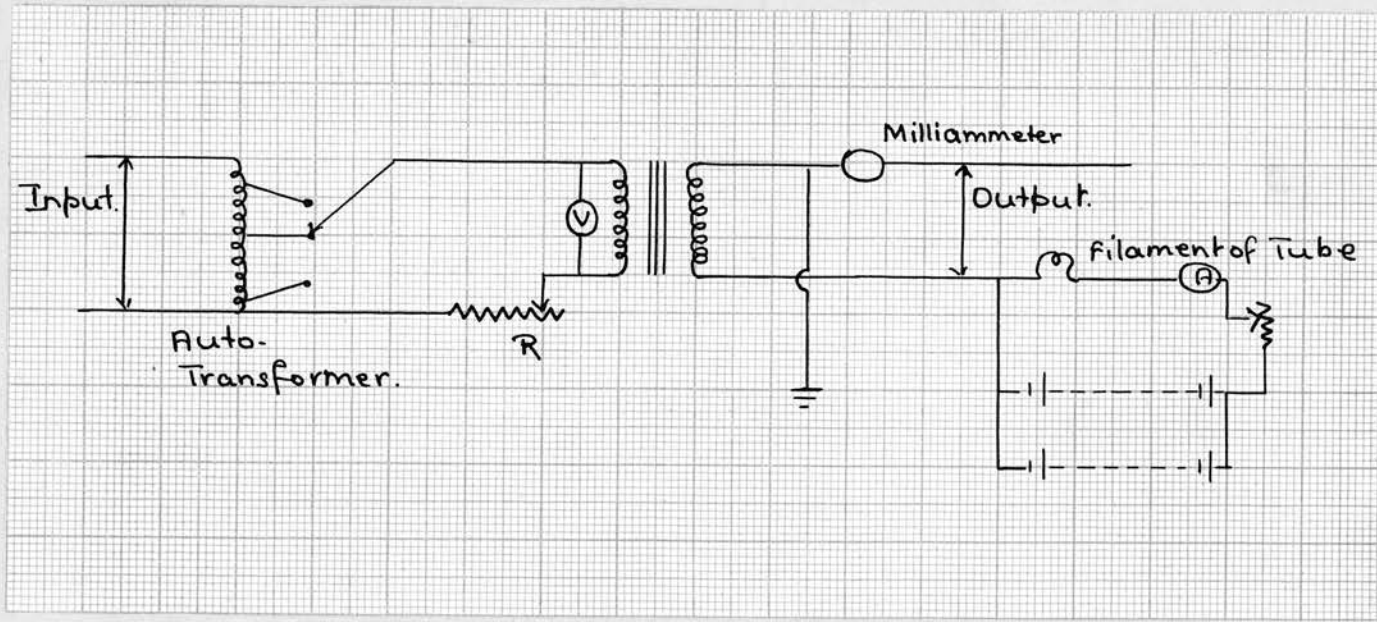A transformer operated from the a.c. mains provided the alternating high potential.

Figure 4.

Figure /

Figure 4 illustrates the main points. An auto-transformer and variable resistance R regulated the voltage to the primary coil of the transformer. One lead from the secondary was earthed and contained the milli-ammeter which measured the current through the tube. This transformer gave a maximum of 90 K.V. The filament of the X-ray tube derived its current from a 12 volt battery of accumulators. This current was regulated by a series resistance and measured by an ammeter.

It was, therefore, unrectified potential that was supplied to the tube which acted as its own rectifier. The values of the peak voltage were measured by a spark-gap in parallel with the tube. This gap consisted of two 10 cm. spheres. As this gap was not permanently connected to the apparatus, a series of careful readings were taken, measuring the peak voltages for various values of primary voltage (as measured on the primary voltmeter V). This was done for each setting of the auto-transformer and for various currents through the tube (·5 m.amp., 2 m.amp., 3 m.amp.). The resulting calibration curves were then used to determine peak voltage, when other conditions were known. These curves were checked against peak-voltage as measured by spark-gap once or twice in the course of the work. The agreement was such that it was considered that this method of determining peak voltage was at least as accurate as that by direct use of spark-gap. It is, of course, obvious that the gap measures the inverse voltage, not the voltage applied to the tube. The difference between these is, however, less than the uncertainty in the determination by the gap.

The /

The direct high tension was produced by the constant-potential-direct-current apparatus which is shown diagrametrically here.
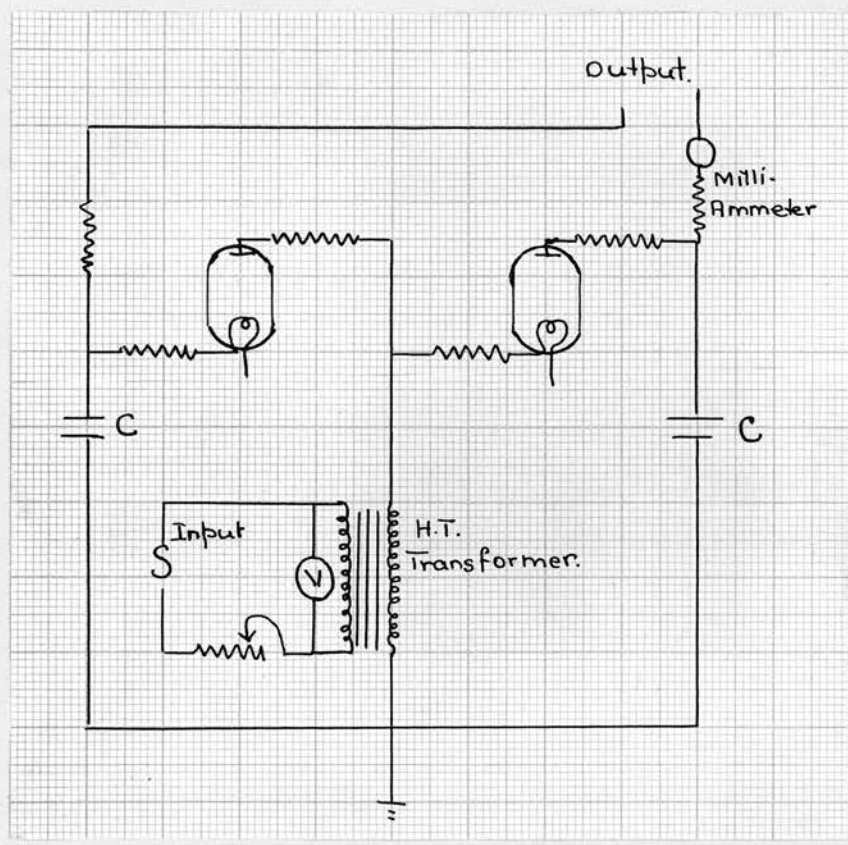

Figure 5.

The primary circuit of the transformer was fed from the a.c. mains and regulated by a series resistance. The voltage was read directly as shown. The valve-filaments had current supplied by step-down transformers which were also fed from the a.c. mains. (Their control is not shown above.) These acted as rectifiers and the resulting series of pulses was smoothed out by the condensers. This arrangement supplied the X-ray tube with twice the transformer voltage. The resistances (apart from that in the primary circuit) were of the order of 50,000 ohms. The maximum voltage which this instrument could supply was 100 Kilo-volts.

A /

A sphere-gap in parallel with the tube measured the secondary voltage. The milliammeter for measuring the current in the tube was placed, as shown, in the negative lead.

One of the features of this work has been the large and varied selection of tubes used to supply the X-radiation. These were of the hot-cathode type and were always used with the cathode rays horizontal. Some details of these tubes are given here for future reference:

(1) Coolidge 18710. This had a tungsten anticathode with its radiating face set at an angle of 45° to the cathode rays. The tube belonged to the old pattern, having a large glass bulb, and no special cooling device. The glass wall of the tube was fairly thin.

(2) Coolidge 43712. There was a molybdenum anticathode set at a very small angle to the direction of propagation of X-rays. Otherwise it was similar to above tube.

(3) Coolidge XP3. This was of the modern cylindrical shape, with an anode of tungsten set at 45° to the cathode stream. Cooling was by fins. The walls were of glass and over the part penetrated by the rays it was ground thinner to prevent severe filtering of the rays. Even so the window was thicker than the walls of the above tubes.

(4) Siemens 234303. This had an anode of tungsten set at 45°. This was cooled by boiling water in a tank behind the target. The thickness of the window was said to be equivalent to /

to 0·7 mm. of aluminium in filtering power.

(5) Siemens VS 1400. Except for the window this tube was identical with the above Siemens tube. In this case there was a Lindemann glass window which permitted penetration of all but the softest rays.

(6) Cuthbert Andrews Tube. The tungsten target was set at 45° to the cathode rays. Cooling was by boiling water.

During the time this tube was used the maximum voltage it would take was 70 KV, owing to faulty insulation. While the thickness of the window was not specified it was less than 0·7 mm.

(7) Philips Metalix Tube 362619. There was a tungsten target set at 45° to the cathode stream. Cooling was by boiling water. There was a Lindemann window.

(8) Philips Metalix Tube 382364. This was similar to the above Philips tube. The only point of difference was in the bull's eye which was larger in Tube 382364. than in Tube 362619. The radiation from this tube was slightly softer than the radiation from the previous tube.

The mass-absorption coefficient of the primary beam as measured in aluminium was taken as a measure of the penetrating power of the beam. This was denoted by $p(\frac{\mu}{\rho})_{Al}$. Owing to the lack of homogenity of the beam (as explained on p. 4) this value varies according to the percentage absorbed in the aluminium as measured by ionization processes. The normal method of measuring this quantity for homogeneous beams is to find /

find the fractional loss in intensity when a thickness x of Al is inserted in the beam. Thus from the equation

$$I = I_0 e^{-(\mu/\rho) \cdot \rho \cdot x}$$

(μ/ρ) may be calculated. This is of course the quantity $_\rho(\mu/\rho)_{Al}$ and the same value is obtained whatever thickness x of Al is used. Obviously in the heterogeneous case $_\rho(\mu/\rho)_{Al}$ would vary for any beam according to the thickness x of Al. In order to obtain one and only one value for a heterogeneous beam we specified that the quantity of Al used was to be that necessary to absorb 50 per cent. of the radiation.

From the above equation we deduce

$$\frac{\mu}{\rho} = \frac{\frac{1}{\rho}(\log I_0/I)}{x}$$

Owing to the finite thickness of the sheets of aluminium (.005 cm.) it was frequently found impossible to reduce the intensity by 50 per cent. exactly. When it was only necessary to know the approximate value of this quantity, the value was calculated from data obtained when the absorption was nearly 50 per cent.; but for accurate work this was insufficient. In these cases several values of $_\rho(\frac{\mu}{\rho})_{Al}$ were measured for values of absorption close to 50 per cent. both greater and less. It was seen that these values lay on a smooth curve when plotted against percentage absorption. The value for exactly 50 per cent. could be read off the graph.

This process involved some considerable expenditure of time and was not carried out for every point at which this value was required. Instead a series of values of $_\rho(\frac{\mu}{\rho})_{Al}$ for /

for varying values of potential applied were carefully determined in this way for a given tube and scatterer. These values when plotted against the potential were found to lie on a smooth curve, as shown in Figure 6.
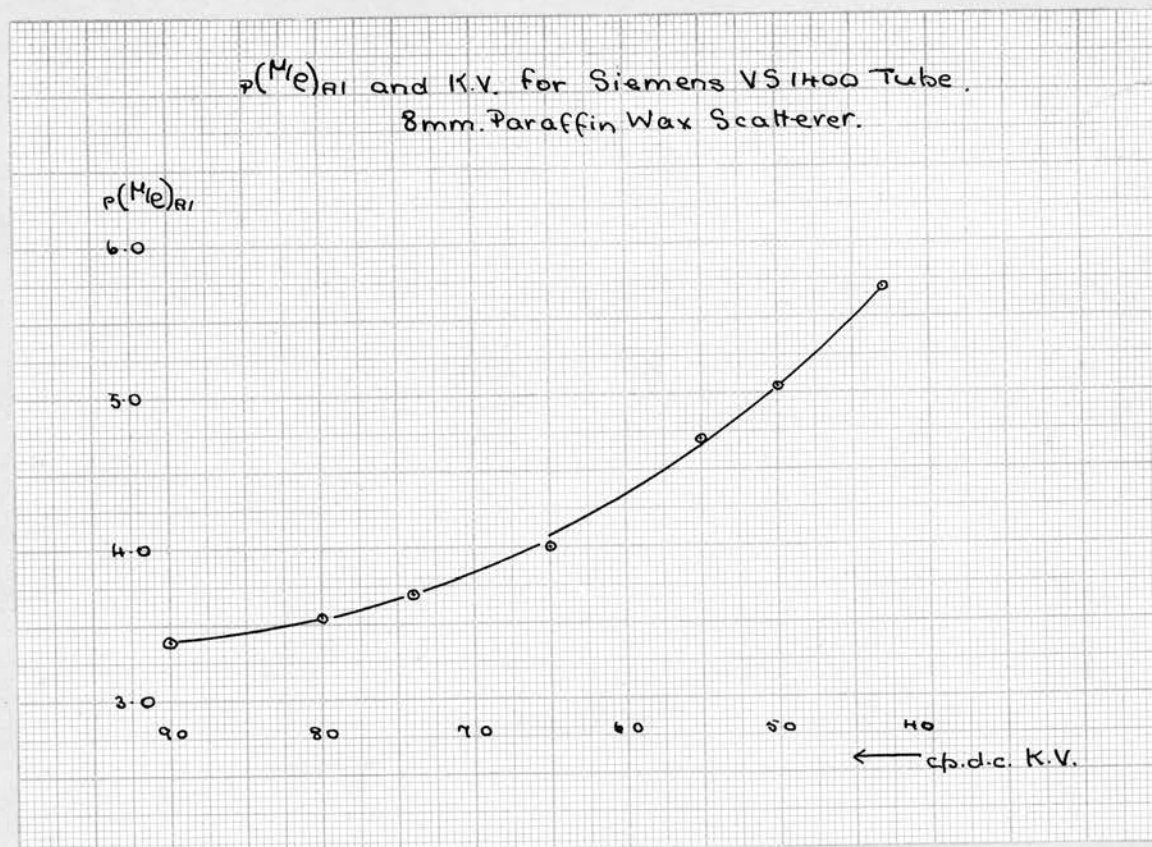

$_p(^M/e)_{Al}$ and K.V. for Siemens VS 1400 Tube.
8mm. Paraffin Wax Scatterer.

Figure 6.

The required value of $_p(^M/e)_{Al}$ at a given K.V. was then read directly off the graph. Experiment showed that variations of tube current and primary aperture within reasonable limits did not affect the value of $_p(^M/e)_{Al}$. For extreme values of current or aperture $_p(^M/e)_{Al}$ was determined again. The values given by the graphs were re-checked from time to time, but no appreciable variation could be detected.

This procedure was only suitable for the case where there was no filtering material between the scatterer and the tube.
In /

In such cases each value of $P\left(\frac{\mu}{e}\right)_{R'}$ had to be found independently.

Before proceding to discuss the results obtained and to draw inferences from these, it will be well to have some idea of the magnitude of the errors involved. In both experiments S/P was plotted as ordinate. The deflection of either S or P was used as standard, i.e. the deflection was from the coincidence of a scale division and an edge of the leaf to another such coincidence. As these could be judged very accurately, the error was small. In measuring the other deflection the position of the leaf was estimated to the tenth of a division. From a consideration of the magnitudes involved we find the maximum possible error of any estimation to be of the order of 1 per cent. The probable error may be calculated from a large number of estimations. This has been shown in detail by Reekie.[2] He finds the probable error to be less than one-third of 1 per cent. for a typical experiemtn. Similar calculations have at various times been made by the writer. On occasion this value has been obtained. Generally it is about two-thirds of 1 per cent., seldom more.

The error in measuring the Kilo-voltage is much larger, as the spark-gap is not an accurate instrument. Even on the c.p.d.c. apparatus the output voltage was liable to ripple. The maximum error of any estimation may be as much as $\pm$ 3 Kv. under unfavourable conditions. Normally, however, the probable error is of the order of $\pm$ 2 per cent. The peak voltage was of course determined /

determined for the a.c. transformer output. A very large number of determinations of voltage was made for each point and the average taken, to reduce the error to the dimensions of that for the c.p.d.c. apparatus.

References

(1) H.A. Bumstead, Amer.J.of Science, Dec. (1911).

(2) Ph.D. Thesis, 1937.

PROGRESSIVE FILTERING EXPERIMENTS.

It was pointed out on pp. 2 and 3 that the classical theory predicts that the ratio Ionisation of Primary/Ionisation of Secondary remains constant whatever thickness of filtering material is inserted into the primary and secondary beams provided exactly equal thicknesses are inserted in the beams. Aluminium or filter paper are used as absorbers, as they can be obtained in sheets of uniform thickness. In all cases after measuring S/P for any given thickness of filters, the filters in the two beams are interchanged and S/P measured again. The average of these determinations(each of which is the average of several) is taken as the experimentally found value of S/P.

The precise prediction of the Quantum Theory has been seen to depend on the constitution of the beam from the tube. The approximate equation derived from this theory is $S/P = Ce^{-yx}$. Where C is a constant, x the thickness of absorber used and y the difference between the absorption coefficients of the secondary and primary beams. Thus for homogeneous incident beams the curve is exponential. Since y varies with x for non-homogeneous beams the curve will not in this case be strictly exponential but will depart the more from that shape the less homogeneous the constitution.
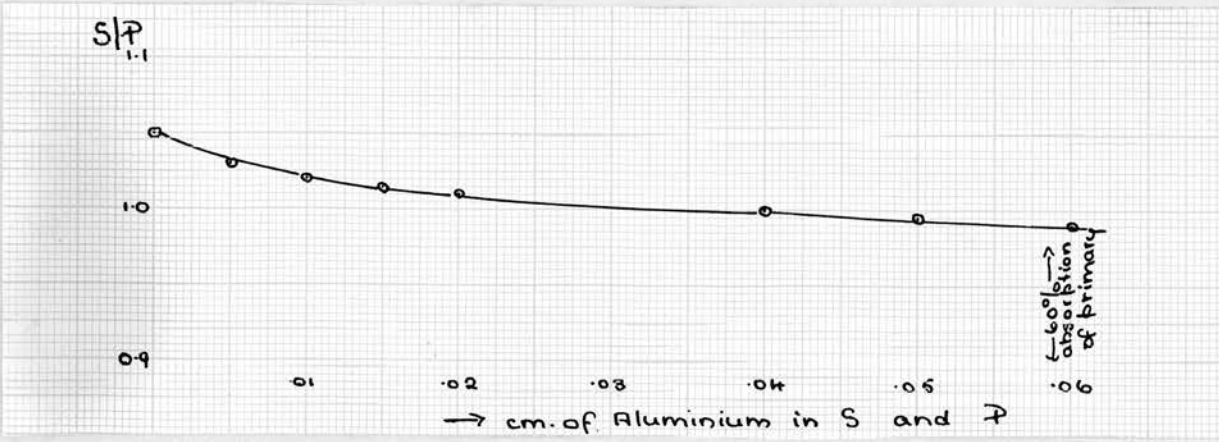

Figure 7.

Figure 7 shows a typical filtering curve. This curve
was obtained when the unfiltered radiation had a mass-absorption
coefficient of 4·0, and ·06 cm. of Al produced a 60% absorption
of the primary beam. This does possess the general appearance of
an exponential curve, i.e. the steepest slope is at the beginning.
The above mentioned curve (and the many similar to it obtained in
the course of the work) would appear to give support to the Quantum
Theory. But in the course of work certain filtering experiments
yielded totally different results. The difference in type was
not due to faulty apparatus or to observational error. The results
could be, and frequently were, repeated at will. Identical condi-
tions invariably produced identical results. Figure 8 shows one
such typical curve.

The difference between this result and the preceding one
is the initial horizontal portion of the S/P curve. When sufficient
thickness of aluminium is present to reduce the intensity of the
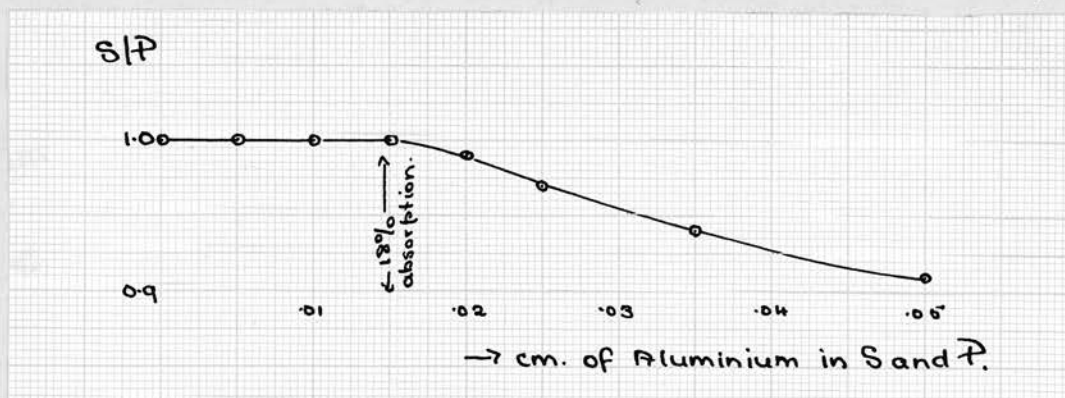

Figure 8

beam entering the primary electroscope by 18%, the ratio begins to
drop in approximately the usual manner. The problem therefore was
to determine what conditions favoured this horizontality and what
rules governed its behaviour.

It is important to realise that this horizontality indicates that the beams entering the chambers are being equally absorbed in the respective chambers.

The following factors are those which might be suspected of influencing the type of the result.

(1) The tube employed.

(2) The current in the tube.

(3) The voltage (A.C. or D.C.) operating the tube.

(4) The material and thickness of the scatterer.

(5) The magnitude and arrangement of the apertures in the apparatus.

(6) The ionisation chambers, their constitution and gaseous
        content.

The voltage applied to the tube was altered while every other condition was kept as rigorously constant as possible. The results of one such experiment are shown in Figure 9.
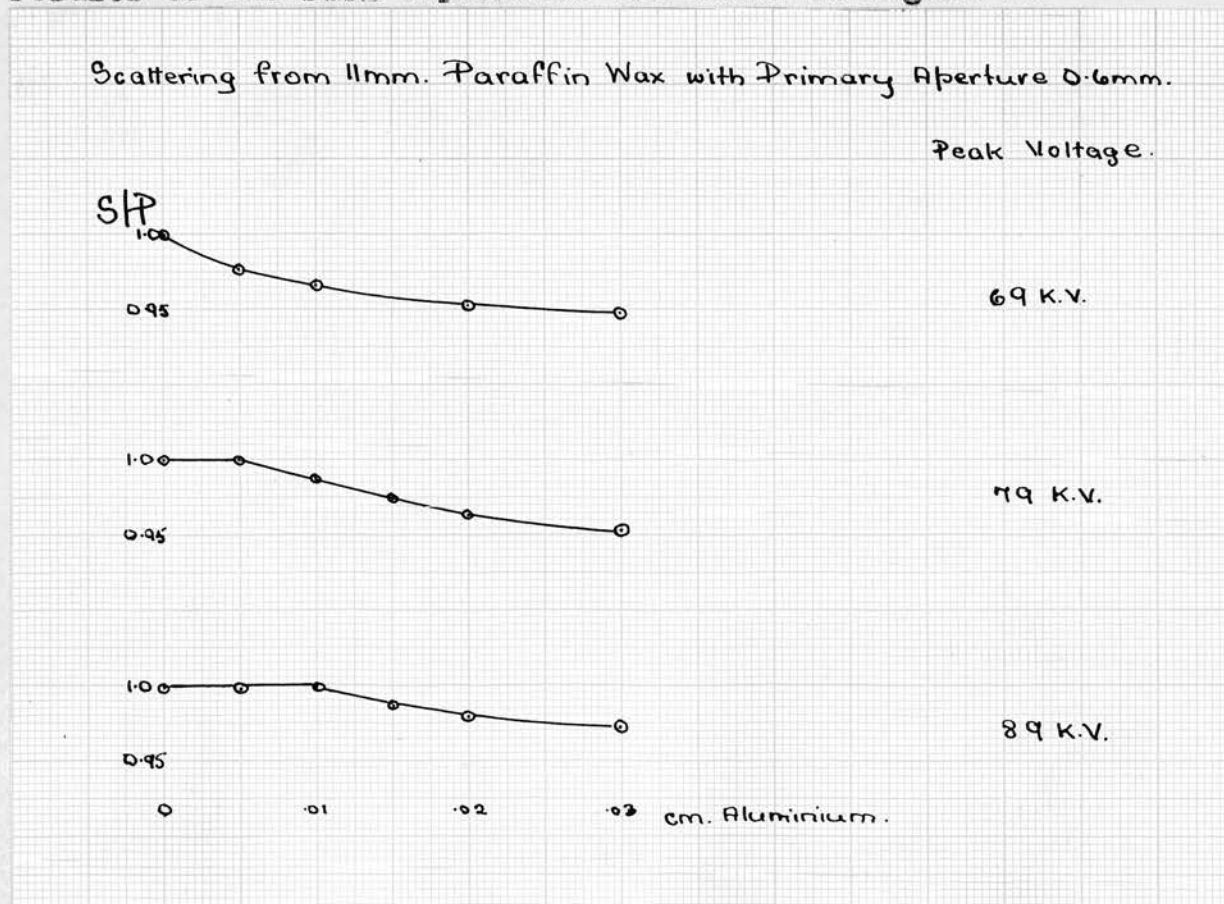

Figure 9

This was carried out on apparatus I with the Coolidge XP3 tube.
The scatterer was 11 mm. Paraffin Wax and the primary aperture a
single circular hole of ·6 mm. in diameter.   A current of 3 m.amps.
was kept running steadily through the tube.   The chambers were
filled with SO_2.   This result was obtained when both electroscopes
were of the simple cubic type.   It will be seen that for low
voltages the curve shows no horizontality.   As the voltage is
increased the horizontality appears and increases with increasing
voltage.   This result is typical of many which have not been
included for considerations of space, but all confirm the fact that
this effect of voltage is not an accidental one in this special
case.

Figure 10 shows that precisely the same effect of increas-
ing voltage is found on apparatus II using the cpdc.apparatus.   This
series of curves was obtained with the Cuthbert Andrews Tube 33983.
The scatterer was 8 mm. Paraffin Wax.   The primary aperture con-
sisted of 4 holes each ·6 mm. in diameter these being situated at
the corners of a square of side 6 mm.   A current of 2 m.amps. was
kept running steadily through the tube.   Air filled the chambers.
As before the horizontal region appears and increases with increasing
voltage.   Emphasis must again be laid on the fact that this result
is not an isolated one.   A consideration of the Figures 9 and 10
shows that this effect of voltage can appear whether the high-tension
source is alternating or direct, that it is not restricted to any one
tube of thickness of scatterer, or one area of primary aperture.
(While the size of the individual holes in each of the above cases
was the same, in one case there were four holes in the other only
one.)

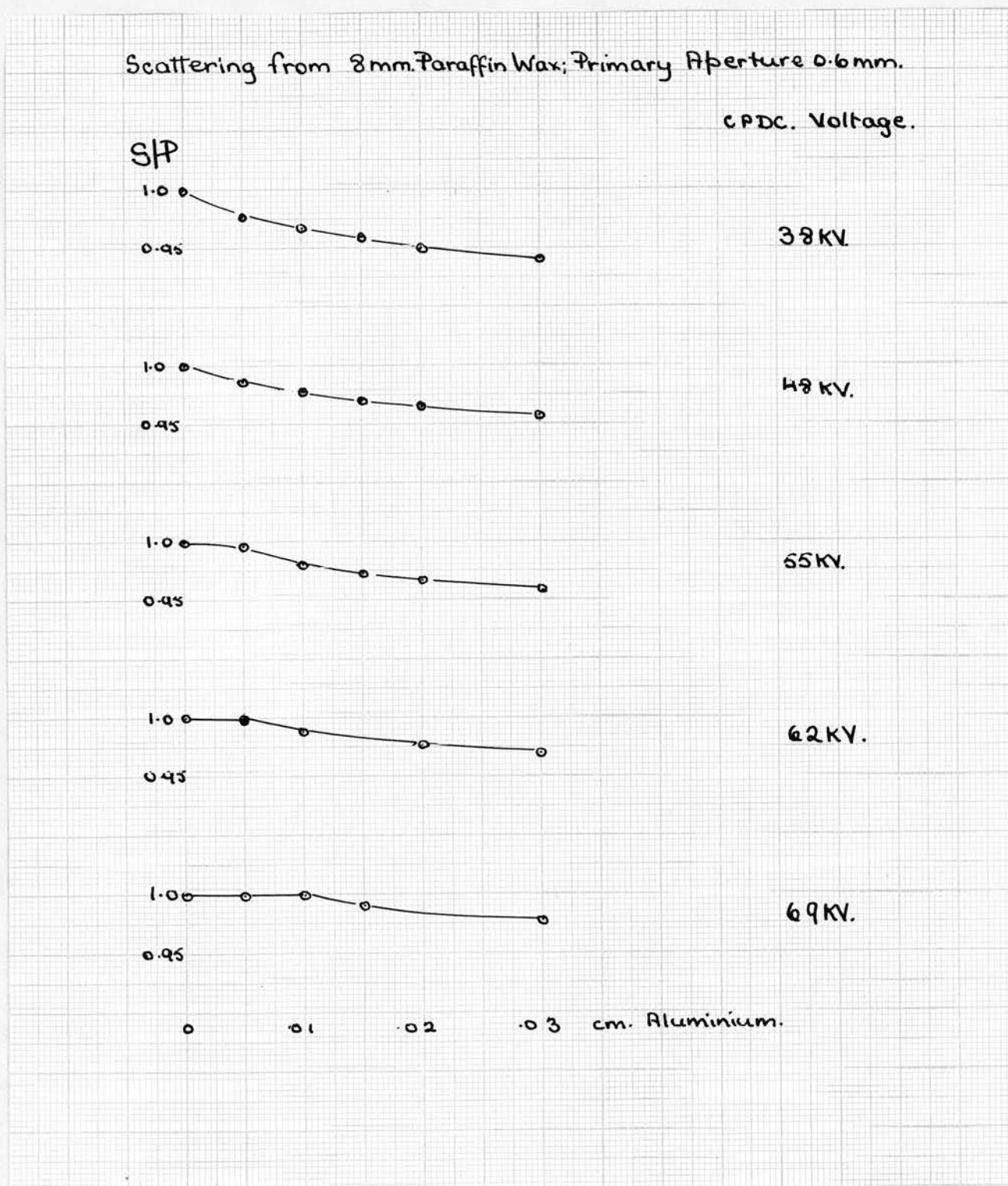Scattering from 8mm. Paraffin Wax; Primary Aperture 0.6 mm.

Figure 10

The next question to be answered is whether horizontality always appears when the voltage is sufficiently raised. Unfortunately we are not in a condition to give an unqualified reply, as there is an upper limit to the voltage we can apply to the tube. Sometimes this limit is set by the tube itself, sometimes it is set by the high tension supply. What would happen beyond this must remain a matter of conjecture. At no time are we ever in a position to attempt extrapolation. Figure 11 was obtained with the Cuthbert Andrews tube which could not be used at a voltage higher than 70 K.V. with safety. No horizontal portion appears on any of these curves. As the voltage increases the curves flatten out gradually but show no sign whatever of initial horizontality. This type of result i.e. what the Quantum Theory predicts, was rather more frequent than the previously described type. The explanation will be more evident when further results have been discussed.
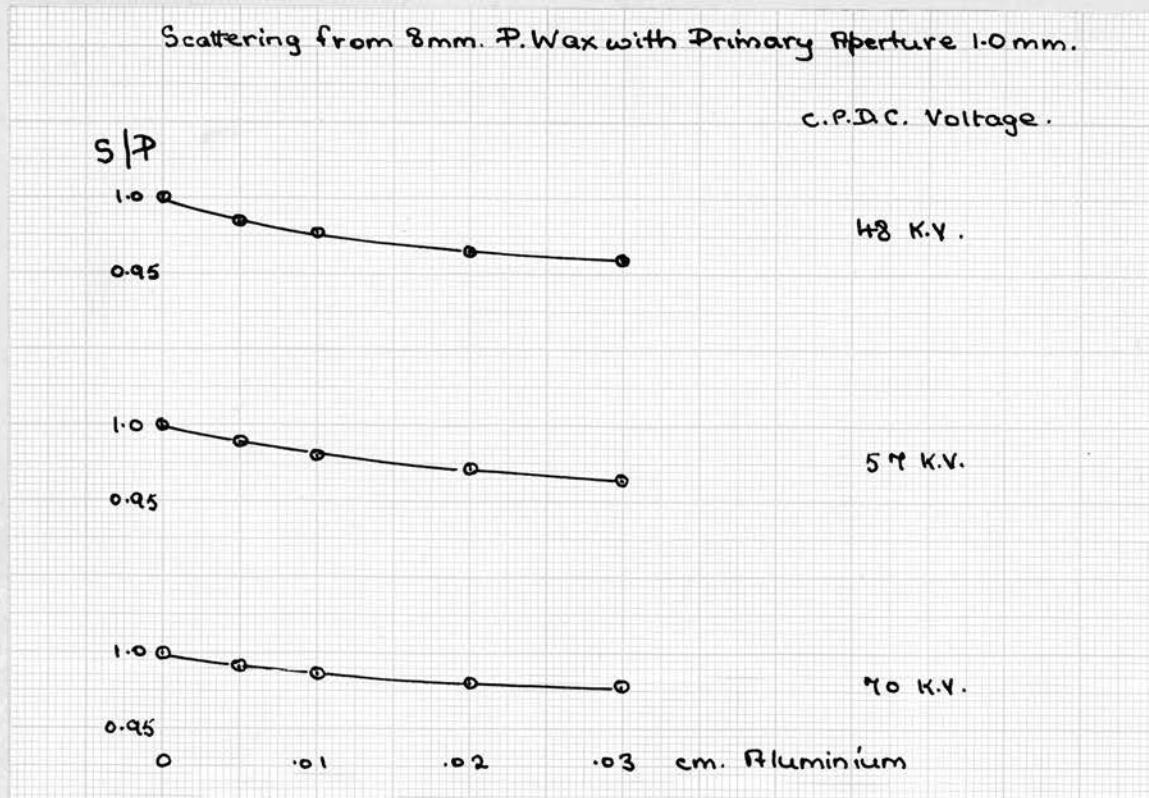

Figure 11

The experiments performed on these lines show that when wide primary apertures are used in conjunction with thick scatterers, no horizontality appears at the highest voltages we can employ. If a very fine slit is used as a primary aperture when a very thin scatterer is in use, some other effect appears to be introduced. At the lowest voltages the filtering curves show no horizontality, but a short horizontal portion appears at somewhat higher voltages as we expect. However as the voltage is farther increased this portion diminishes in length and finally disappears, so that under these conditions the curves for the highest and lowest voltages show similar shapes. (This point is developed later pp.94-96) It is thus obvious that factors other than the voltage do influence the shape of the curve. These must be fully investigated. The influence of the voltage on the shape of the curve may be summarized as follows; an initial horizontal portion of the filtering curve is found to appear and increase as the voltage operating the tube is increased. Exceptions are found to this rule with extreme dimensions of scatterer thickness and aperture diameter.

Experiments were then undertaken, varying only the thickness of the scatterer. Figure 12 shows the result of a series of experiments on apparatus I when the primary aperture was a single circular hole of 0·6 mm.diameter. The a.c. peak voltage was maintained at 80 k.V. It will be seen how as the thickness of the scatterer is increased the thickness of the filters over which S/P remains constant decreases. It is unfortunate that the thinnest sheet of aluminium available of sufficient uniformity to be used for filtering is comparable with the thickness for which S/P remains constant. While both the 8 mm. and the 11 mm. curves depart from

horizontality between the first and second filtering sheets it is
obvious from the positions of their respective points for 0·01 cm.
aluminium filters that had finer filters been available the hori-
zontality would have been longer for the 8 mm. curve than for the
11 mm.

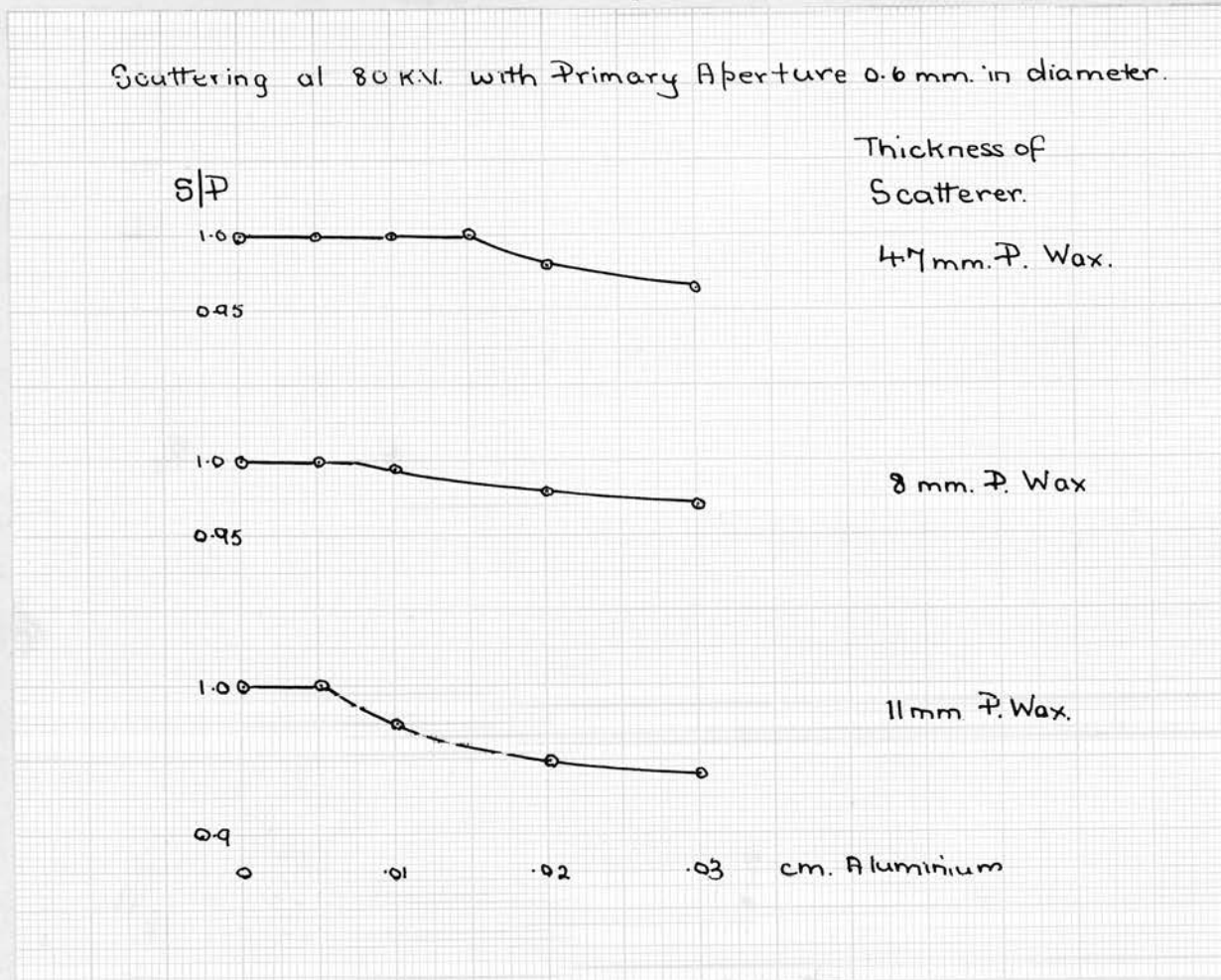This effect of altering the thickness of the scatterer

Figure 12

is amply verified by many other experiments.

It was of interest to discover whether the exception
mentioned on page ³⁵ was due to the thinness of the sheet of
radiation entering the primary ionisation chamber through the slit,
or to the thinness of the scatterer, or the high voltage separately
or whether it was due to a combination of these. We therefore used

a lower voltage and found the result of combining the other two factors, i.e. fine slit and thin scatterer. Figure 13 shows that no abnormality appears when these two factors are combined. The result here agrees with the previous statement, that the extent of constant S/P decreases with increasing thickness of scatterer. Thus a narrow slit and thin scatterer combined have given no abnormality. Nor is such abnormality due solely to high voltage as the Figure 14 shows.
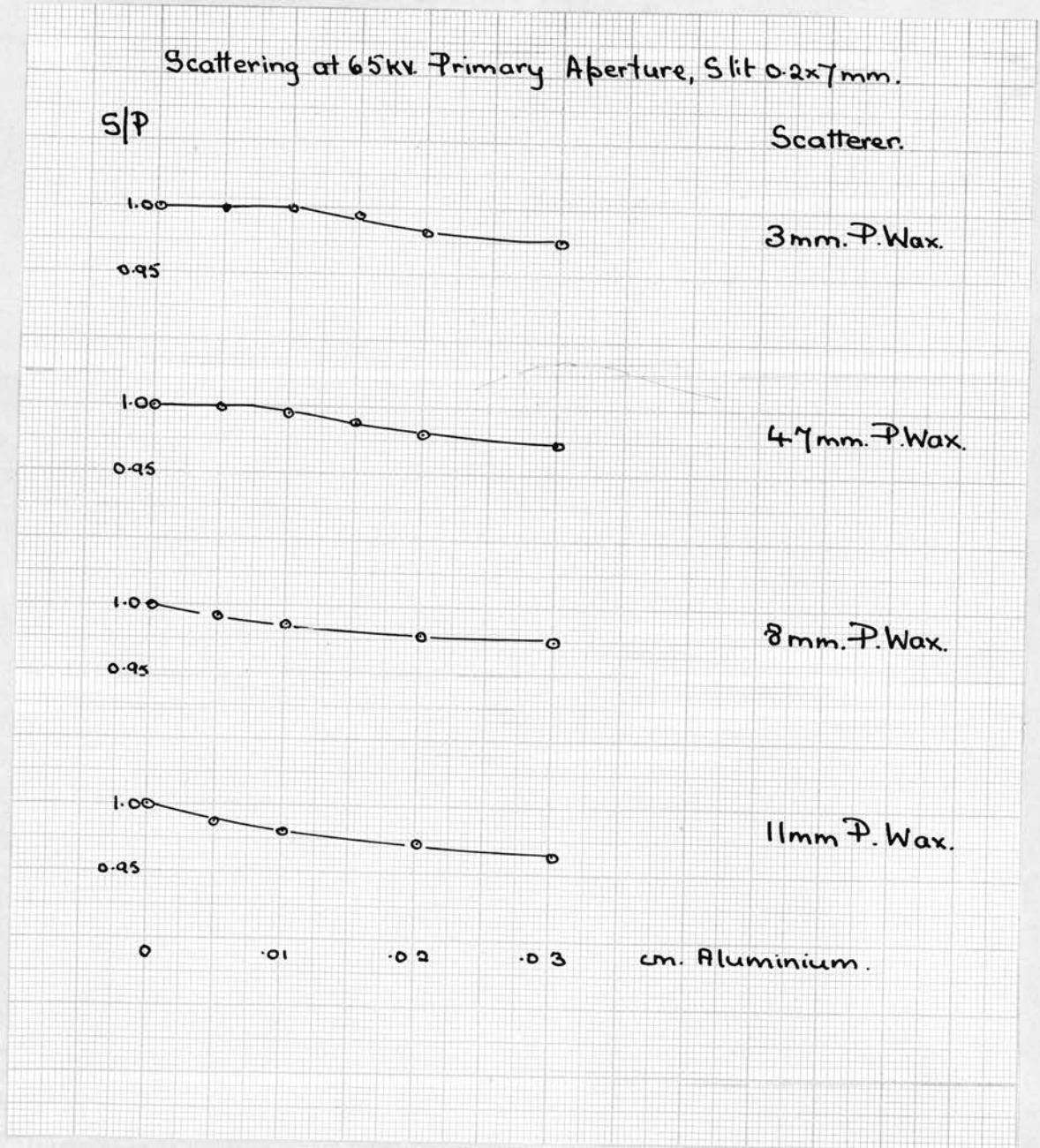

Figure 13

These experiments were carried out on apparatus I with Coolidge XP3 tube, excited by ac. transformer. Thus we are led to the conclusion that exceptions to the general rules of producing horizontality i.e. horizontality appears and increases with a) increasing voltage. b) decreasing thickness of scatterer, are only found when the conditions combine a very high voltage, thin scatterer and fine slit aperture.

Scattering at 86 K.V. with Primary Aperture 0·6mm.

S/P

Thickness of Scatterer.

1·00

0·95

4·7mm. P. Wax.

1·0

0·95

11 mm. P. Wax.

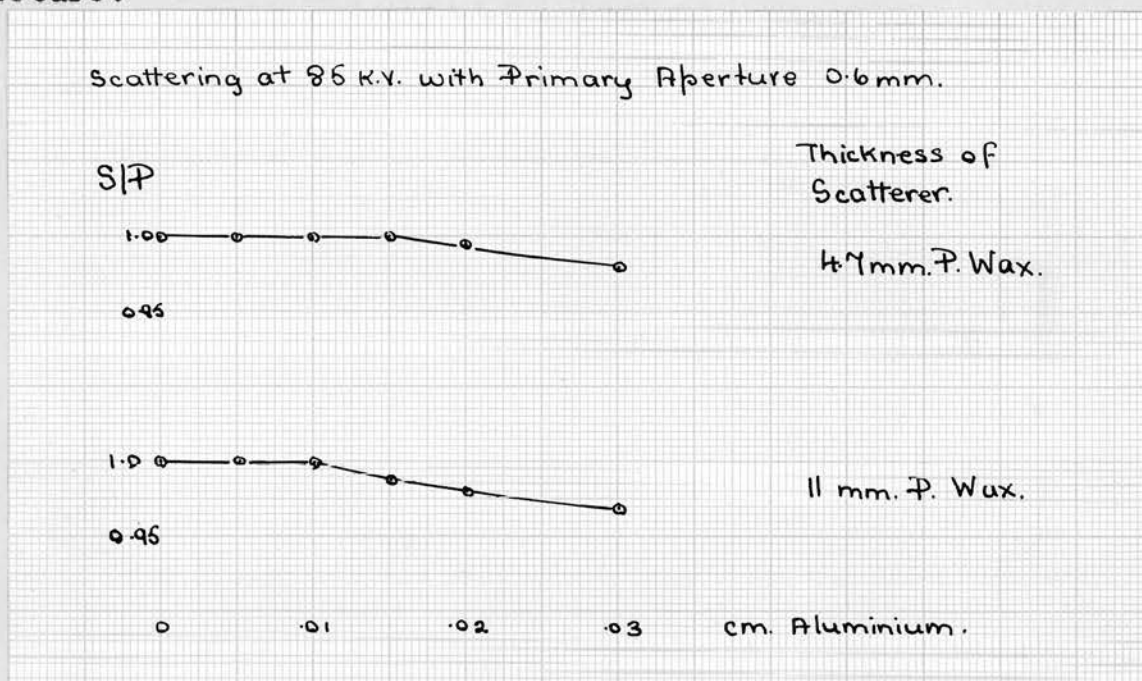0   ·01   ·02   ·03   cm. Aluminium.

Figure 14

The effect of altering the primary aperture was fully investigated. Confining ourselves to circular apertures only, two alternative primary apertures - both cleanly drilled circular holes, - were much used, owing to the convenient values of S/P they gave. One was of 1·0 mm. diameter and the other 0·6 mm. Figure 15 shows that for the given conditions the horizontality was only produced when the smaller aperture was used. A very marked difference is obvious between the curves. This result was obtained on apparatus I when the tube was excited by a.c. transformer. That this aperture effect

is independent of method of excitation is shown by Figure 16 which gives the results obtained on apparatus II when cpdc. was applied to the tube.   The difference in slope between the curves on these two figures may be put down to the different thickness of scatterer.

Scattering from 4·7mm. Paraffin Wax at 40. K.V.

S/P

Diameter of
Primary Aperture.

1·0

0·95

0·6 mm.

1·0

1·0 mm.

0·9

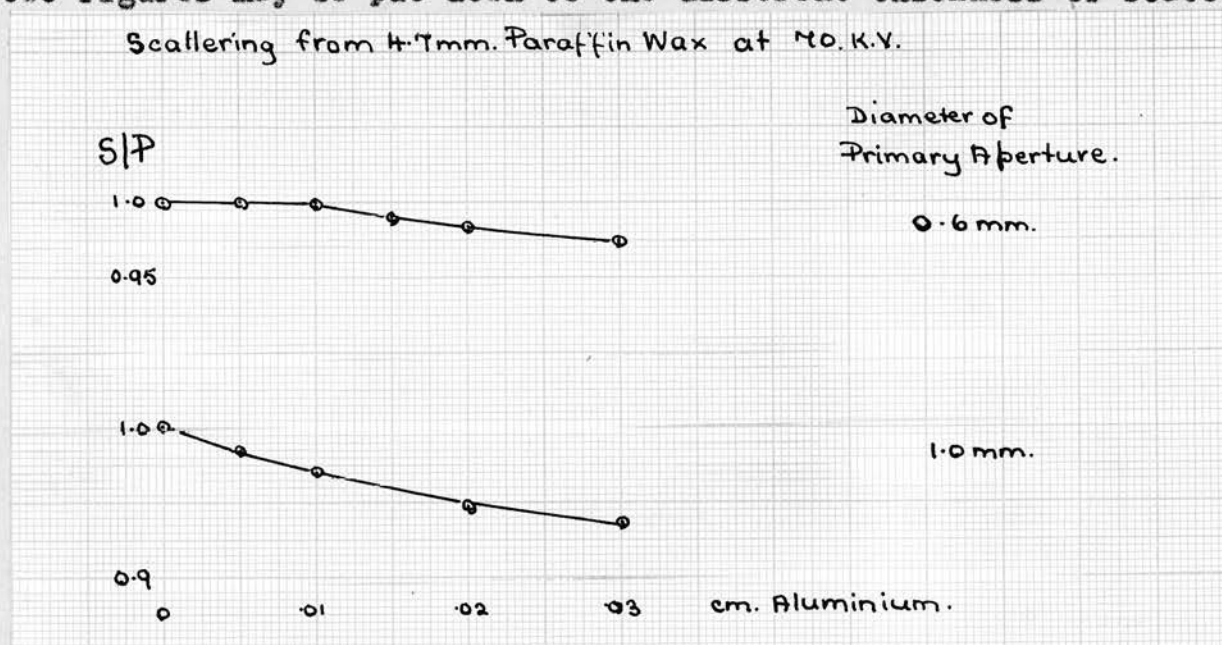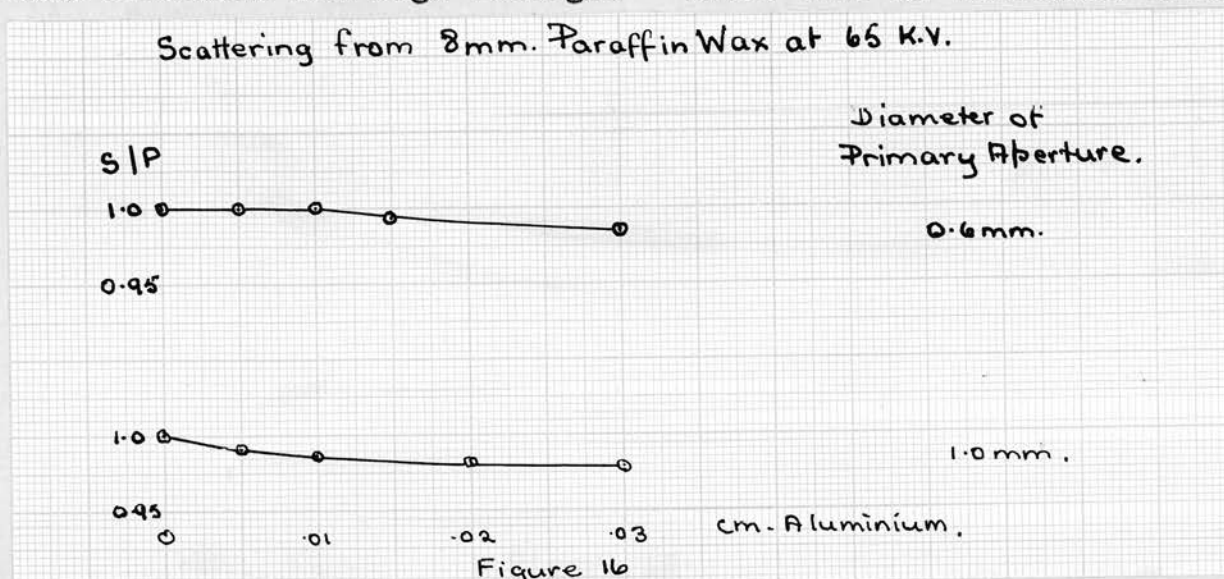0   ·01   ·02   ·03   cm. Aluminium.

Figure 15

The above experiments show how under certain conditions when no horizontality appears with one aperture the use of a smaller aperture will produce it.   Experiments however suggest that horizontality cannot invariably be produced merely by diminishing the size of the primary aperture.   A more general statement cannot be made as no aperture finer than a slit of 0·1 mm. x 7 mm. was used. Horizontality appeared by the use of a finer aperture when the values of the voltage and the thickness of the scatterer were favourable to its appearance, by the rules stated above.

On p. 31 we specified certain conditions which might influence our results.   So far it is obvious that the conditions favourable for the horizontal portion of the S/P curve, are high voltage, thin scatterer and small aperture.   An exception must be

made in the case of the narrow slit aperture when accompanied by a thin scatterer and high voltage.   (This will be discussed later).

Scattering from 8mm. Paraffin Wax at 65 K.V.

S/P

Diameter of
Primary Aperture.

1·0

0·6 mm.

0·95

1·0

1·0 mm.

0·95

Cm. Aluminium.

Figure 16

The effects produced by changing the x-ray tube, the current through the tube, and the sizes of apertures (other than the primary aperture) must now be considered.   The current could be varied over a wide range, but when small currents are used, the duration of the experiment must increase thus making the normal electrical leaks more significant.   Large currents might obviously produce such intense beams that saturation could not be obtained in the ionisation chambers under the actual working conditions.   However a 6-fold variation of current (from 0·5 m.amps. to 3·0 m.amps.) was made without altering the ratio S/P for any one point.   This signifies that over this range saturation was obtained.   Since no value of S/P was varied, by alteration of the intensity of the current, the latter had no effect on the shape of the curves over this range.

The apertures between tube and scatterer were varied to give a bigger or smaller patch of radiation on the scatterer, but in no case was any variation seen in the S/P curve.   Similarly no difference could be seen when the secondary apertures were altered.

The effect produced when the tube was changed is somewhat more complicated.   A curve taken with the Coolidge XP3 tube at 89 K.V. (peak) and 11 mm. scatterer and 0·6 mm. primary aperture, was repeated with the Siemens VS 1400 tube.   These tubes gave streams of radiation of very different constitution, owing to the different filtering powers of the windows in the tubes.   In both cases the anti-cathode was of tungsten but while the Siemens had a Lindemann window, the Coolidge window was of glass.   As Figure 17 shows there is a longer horizontal portion in the curve obtained
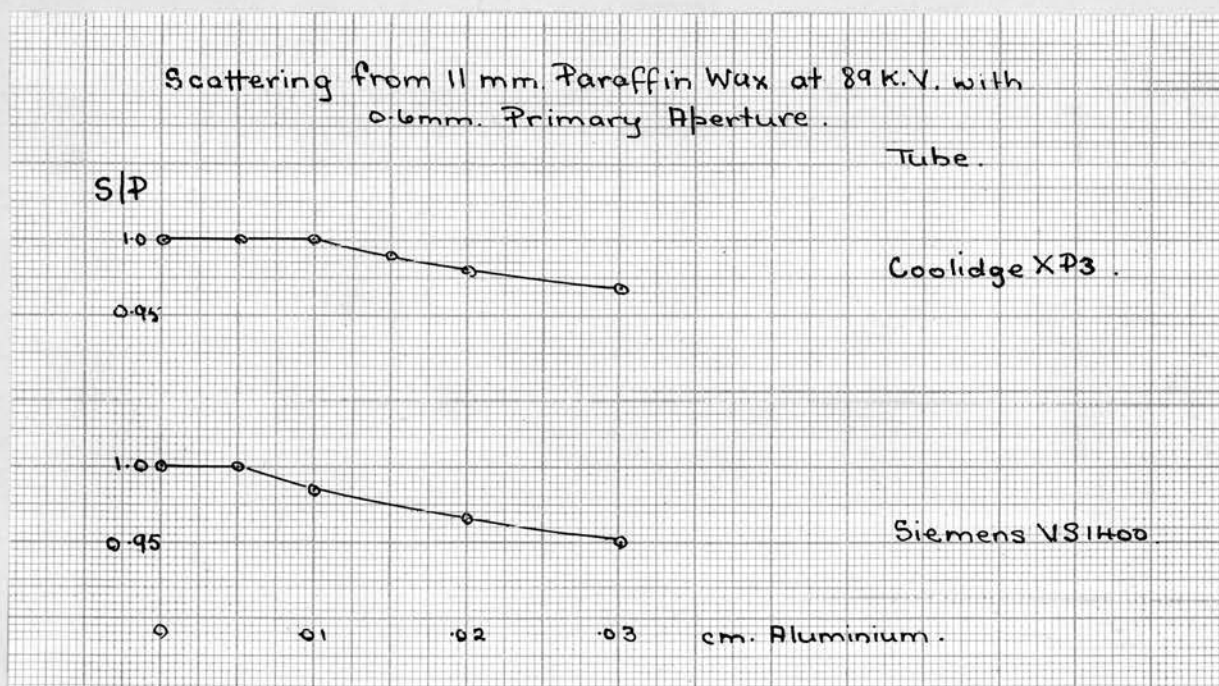

Figure 17

from the Coolidge tube, but the horizontality disappears in each when approximately the same percentage of primary radiation has been filtered out.   Owing to the much softer beam from the Siemens tube, a smaller thickness of Al. will suffice for it than for the Coolidge XP3.   This result appears to be quite general for different tubes. The length of the horizontal portion varies, being longer for tubes

giving harder beams.   Tubes, which give approximately the same
beams are indistinguishable in this connection.   That this effect
is small is shown by the above figure.   As these two tubes were
chosen as giving the greatest possible variation in constitution,
there is very little difference between any two tubes not having a
Lindemann window.

The result of extreme softening of the primary beam is
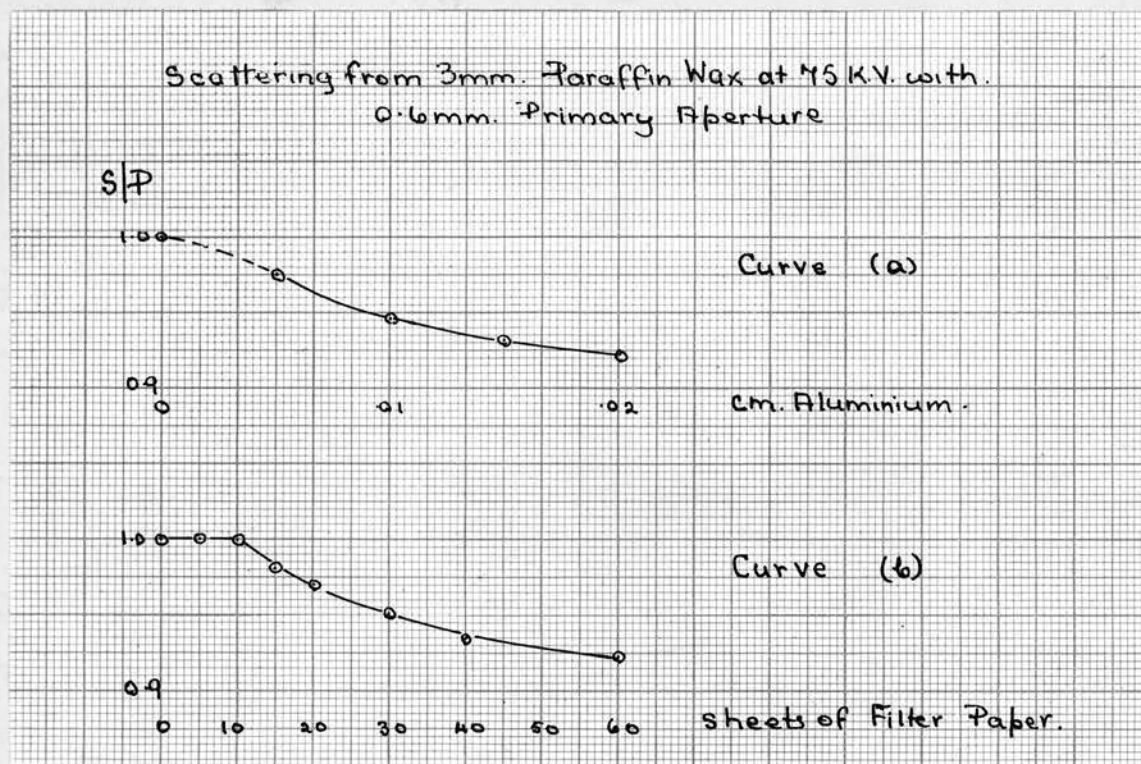shown in Figure 18.   Here we have a filtering curve - (a) which is

Figure 18

the result of an experiment done at 75 (peak) Kilo-Volts on apparatus
I with the Siemens VS 1400 Tube, when the scatterer was 3 mm. wax and
the primary aperture 0·6 mm. in diameter.   No horizontality at all
is seen - there being a drop of over 2% in S/P when the thinnest
filter is used.   From the above conclusions on the effects of
voltage, scatterer and aperture it is obvious that this is a region

where horizontality is to be expected.   It is however possible that the radiation is so soft that the first filtering sheet is absorbing such a large percentage of radiation that the filtering processes have already passed the extent of the horizontality.   Filter paper was therefore used to filter the beams instead of aluminium. Experiment showed that 30 sheets of filter paper were equivalent in absorbing power to •1 mm. Al.   Thus the curve (b) was obtained. It can be seen that there is a short horizontal region which disappears at about the 10th sheet of paper when 11% of the primary is absorbed as measured by its ability to ionise.   At points where the number of sheets of paper is a multiple of 15 i.e. is equivalent to a number of sheets of •005 cm. Al. it can be seen that there is agreement between the curves.

This raises the question of whether by using sufficiently fine sheets of filtering material horizontality could be shown to be present, to a greater or less extent in all cases.   In order to investigate this point, experiments were carried out in under conditions which had previously shown no horizontality.   These showed that when a very small thickness of filter was used the ratio dropped at once.   Naturally for points on the extreme left of the curve for which the difference between S/P and its initial value was smaller than the error no conclusion can be made.   It is however certain that this horizontal portion (if it exists at all) is extremely short, and the amount of primary radiation absorbed over this is not more than 5%.   Thus we may safely say that there are combinations of factors which produce initial horizontality in the filtering curve and combinations of factors which do not.

The physical meaning of this horizontal portion of the

filtering curves is that the beams are being equally absorbed in the ionisation chambers. The reality of this horizontality is discussed later, but it must be emphasised here, that this appears under conditions where the greatest negative slope of the curve is to be expected from theory. Figure 16 shows how very different are these two types of curves. There is one other effect not already discussed which must now be mentioned. Several of the workers in this laboratory have found that over a period of time the shape of an experimentally found curve would change e.g. conditions which would on one occasion give a horizontal line in the graph, would on another give a smooth curve. This indicates the influence of some
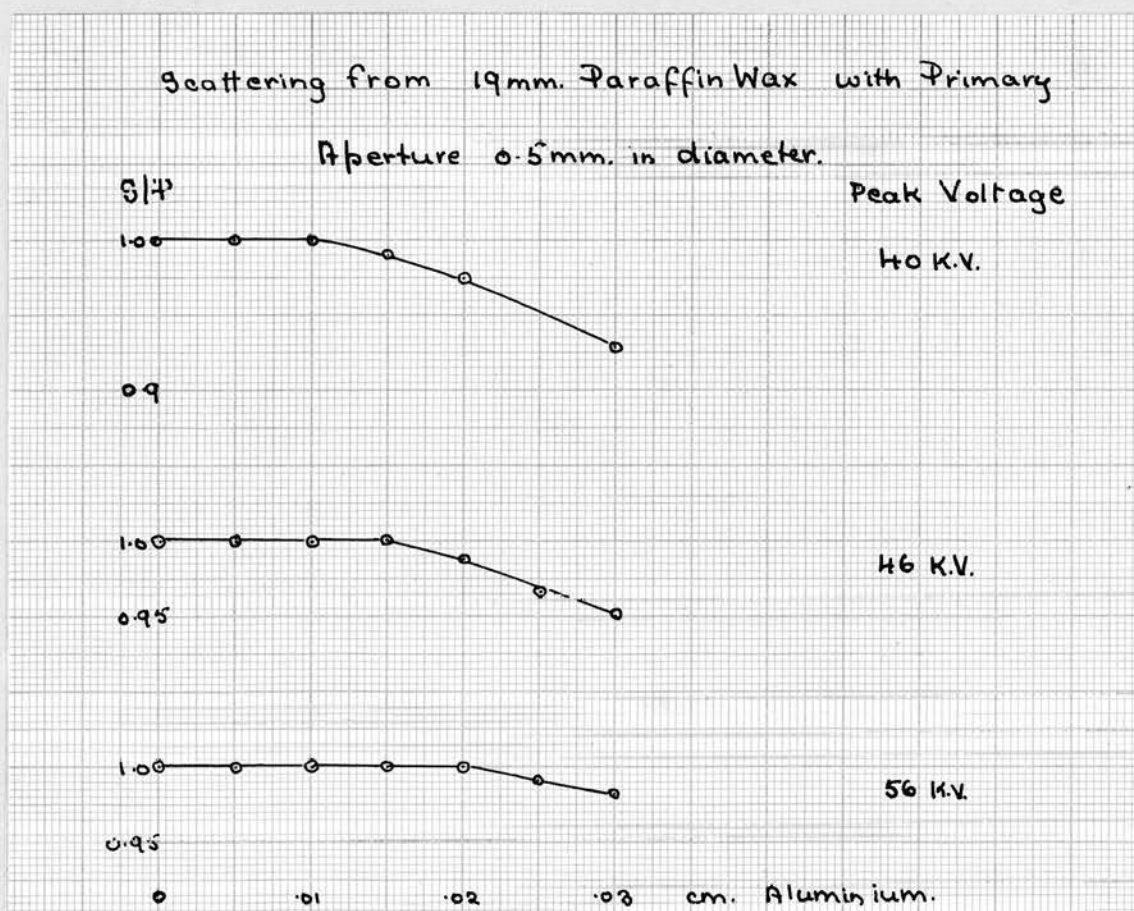

Figure 19

factors, at present unknown. In the present work on apparatus I and II however, results have always been completely reproducible,

within the limits of error; with one notable exception.   This
occurred in the original experiments on the rules governing the
control of the horizontal portion of the filtering curve.   These
experiments were made with apparatus I using the Coolidge 18710 tube
and a tube current of 1·0 m.amps.   The values of voltages, thickness
of scatterer and the size of the aperture are marked on the individual
graphs.   These curves agree in principle with those already given
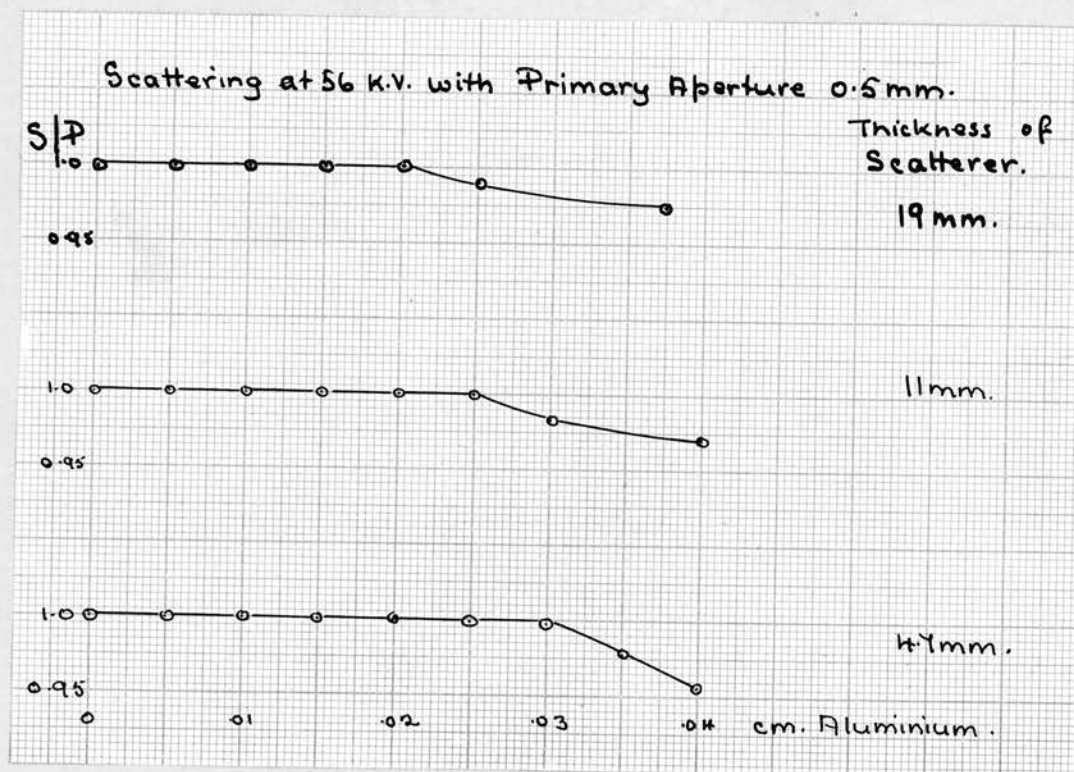i.e. the horizontal portion increases in length with increasing

Figure 20

voltage, decreasing thickness of scatterer and decreasing size of
individual apertures.   They are shown in Figures 19, 20 and 21.
These curves were all obtained within a period of five weeks. During
that period any of these curves could be reproduced within narrow
limits by the appropriate arrangement of the apparatus.   There was
no suggestion of any change whatever in the shape of the curves at

that time.   After some twelve months it was found that no horizon-tality was present at any voltage or with any aperture,   when 19 mm. of wax was used as a scatterer, i.e. the above conditions which showed marked horizontality originally were no longer able to produce it, although other conditions did produce it.

Figure 21

Certain alterations had been made in the apparatus in the interval. The cubical secondary electroscope which was used to obtain the graphs on Figures 19, 20 and 21 was replaced by one of a Wilson tilted type. This necessitated the moving of the secondary ionisation chamber towards the scatterer through a distance of approx. 1 cm. There is the possibility that this change in the apparatus may have influenced the results. It must be recorded at this point that direct experiments on the influence of the electroscope on the shape of the curve have always given a negative result. The effect of the apparatus on the results will be discussed fully later (p. 80-86).

This suggestion gains weight when the results of filtering experiments on apparatus III are considered. No initial horizontality has ever been observed in any filtering experiment on this apparatus.

Briefly we may sum up the results of the filtering experiments thus: Under certain conditions the results approximate to those anticipated by the Quantum Theory. Under other conditions the graph of S/P against thickness of filter has short initial horizontality. The conditions favouring this horizontality are, within limits -

        (1) High Voltage.

        (2) Thin scatterer.

        (3) Fine primary aperture.

It must be admitted that this horizontality i.e. the equality of absorption, depends to some extent on the apparatus employed.

SCATTERING EXPERIMENT.

In this section it is proposed to deal with the results of the scattering experiment as mentioned on pp. 5,6,7. of the Introduction.

The layout of the apparatus was the same as that for the filtering experiment. The radiation passed through a scatterer set at 45° to the beam, the secondary and primary measuring apparatus were arranged to compare the ionisation produced by the scattered rays from the back face of the scatterer with that which passed without any deviation. The ratio S/P was plotted against the voltage operating the tube, as this was varied over the available range. As the radiations from different tubes operated at the same voltage are very different, owing to the different filtering powers of the windows, (as indeed are the radiations from the same tube operated at the same voltage from ac. and dc. sources) it is often felt that it is unsatisfactory to plot against kilo-voltage which only specifies the maximum energy of the radiation. The mass-absorption coefficient of the radiation can be used instead as this is a measure of the average penetrating power of the beam. This is not entirely satisfactory either, as it is possible to obtain two beams of identical $\rho\left(\frac{\mu}{e}\right)_{Al}$ whose behaviour in other respects is quite different. Many of the results given have been plotted both against the kilo-voltage of the tube, and the mass-absorption coefficient of the primary beam. In some cases one method is more satisfactory than the other, and the curve is shown plotted in that way.

The general character of the curves is unchanged by the

method of plotting provided, if $_P\left(\frac{\mu}{e}\right)_{Al}$ is shown as increasing
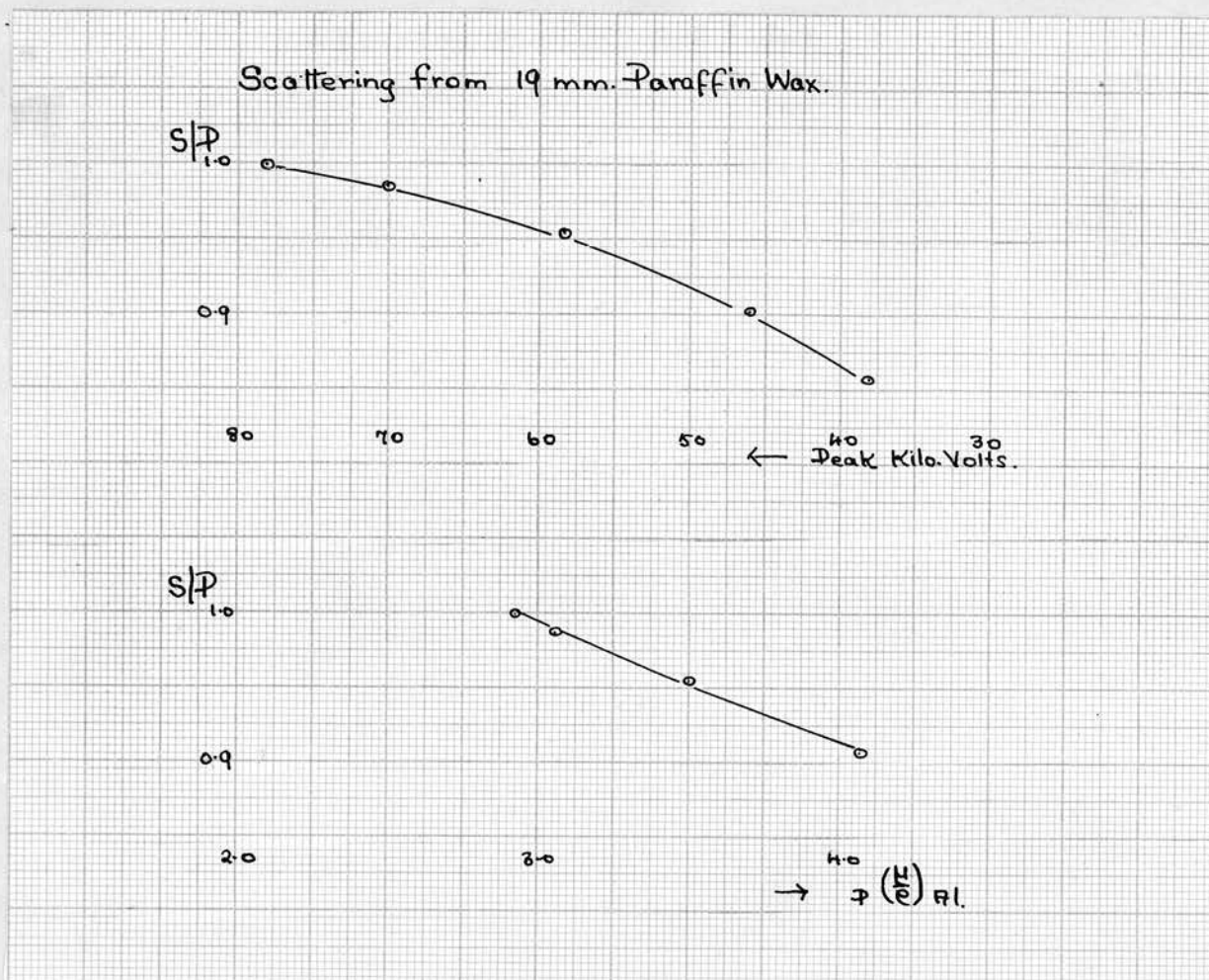

Figure 22.

from left to right, the kilo-voltage must be shown as increasing

from right to left, since $_P\left(\frac{\mu}{e}\right)_{Al}$ decreases when KV. increases.

Naturally the shape of the curved portions of the graphs is

modified by the change since Figure 6 shows that there is a

nonlinear relation between these two quantities.

Figure 22 shows a typical scattering curve plotted in

both ways. It is seen that there is no discontinuity of ratio

or of slope as the tube has its output varied by varying the

exciting voltage. This smooth type of curve, (concave downwards

when plotted against kilo-voltage, concave upwards when plotted

against mass-absorption coefficient), was that most usually
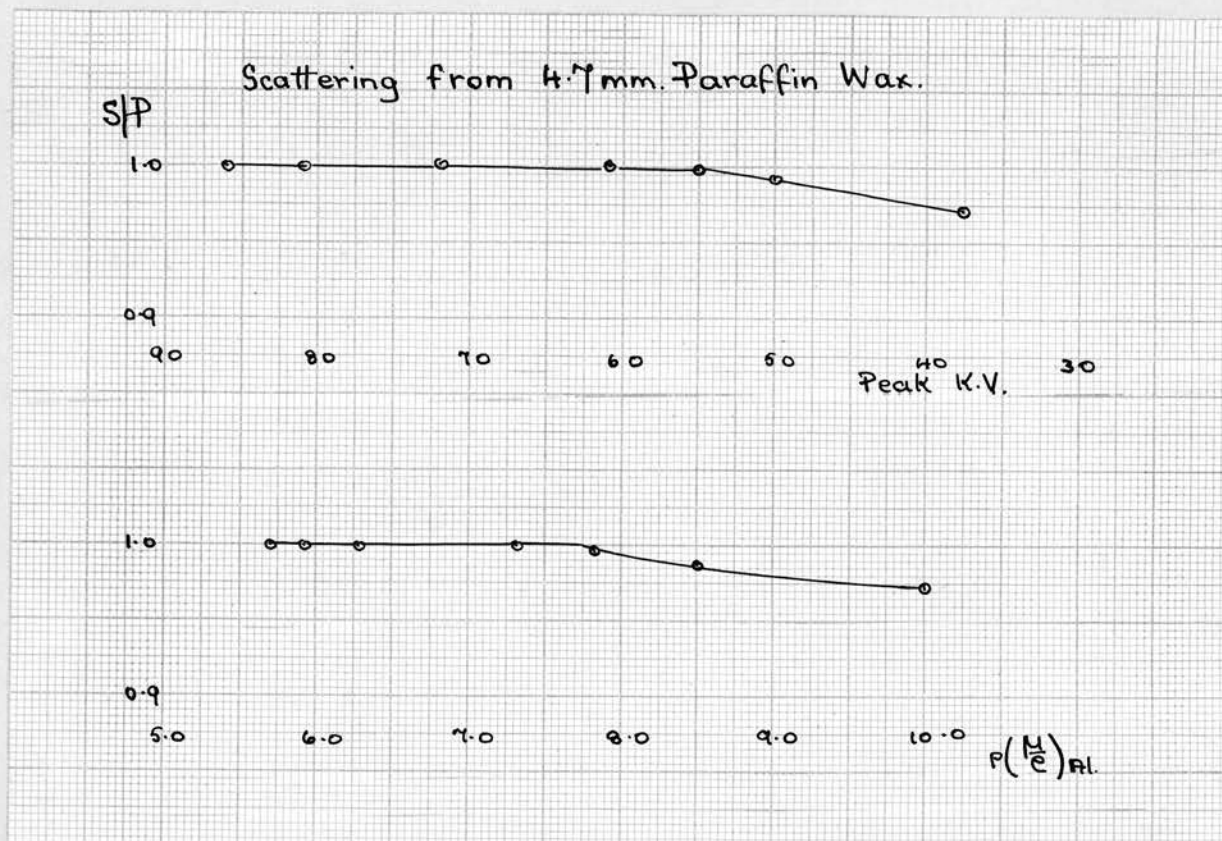
obtained, and may be taken as typical.

Figure 23.

Figure 23 however shows that another type of result

may also be obtained. At low voltages an increase in voltage

$\left[\text{decrease in } {}_P\left(\frac{\mu}{e}\right)_{Al}\right]$ produces an increase in S/P. This

change is approximately a linear one. After a certain critical

voltage, and associated ${}_P\left(\frac{\mu}{e}\right)_{Al}$ the ratio S/P remains constant

for higher voltages i.e. harder beams. In many cases the readings

were absolutely constant, over the horizontal part and no change

could be detected at all. (Where very small variations did appear

these were not systematic, and frequently disappeared entirely on

repetition). Over the region of voltage where the change from

horizontality to the smooth curve took place, the readings were

repeated many times, and in different sequence in order to be absolutely certain of this discontinuity of slope. There seems no ground for supposing that this horizontality is unreal - that the line is part of a smooth curve of small curvature. As stated above no systematic change of S/P with voltage has ever been noticed. Within the limits of error (which may be very small cf. p. 27) the curve is certainly horizontal. Owing to the frequent appearance of this type of result, this scattering experiment is often referred to as the Horizontal Line Experiment.

It was necessary to discover what conditions favoured the appearance of this horizontality, and whether a systematic change in these conditions would produce a systematic variation in the extent of horizontality. The conditions which might influence this were considered to be -

(1) The tube employed and its method of excitation.

(2) The current in the tube.

(3) The material and thickness of the scatterer.

(4) The magnitude and arrangement of the apertures in the apparatus.

(5) The ionization chambers, their constitution and gaseous content.

Experiments were performed with the thickness of the scatterer as the only variable. The scatterers available were of paraffin wax of thicknesses, 19 mm., 11 mm., 8 mm., 4.7 mm., and 3 mm. Any given number of sheets of filter paper could be fitted into holders and substituted for paraffin wax.

Figure 24 shows the result of a series of experiments on apparatus I using the Siemens VS 1400 tube when the primary aperture was a single hole 0.6 mm. in diameter, the gas ionized being SO_2

at atmospheric pressure, and the tube being excited by an ac. transformer.   A change in scatterer is seen to alter the shape of the curve, the horizontality increasing as the thickness of the scatterer is decreased.   One interesting result can be deduced from this series of curves.   A graph of the value of the critical kilo-voltage (i.e. that value above which the ratio is constant) plotted against the thickness of the scatterer used to obtain the curve, shows that a small change in thickness for a thick scatterer produces a bigger change in the critical voltage than the same change in thickness for a thin scatterer, i.e. to decrease the thickness beyond 3 mm. does not result in a much longer horizontal line, if plotted against K.V.   There seems to be a limiting K.V. below which there is no horizontality however thin the scatterer. This is only a tentative suggestion owing to the difficulty of extrapolation when there is so much uncertainty in the values of the K.Voltage.   But if we plot against $\rho\left(\frac{\mu}{e}\right)_{Al}$ instead of kilo-voltage the length of the horizontal portion increases rapidly with decrease in the thickness of the scatterer, and this for two reasons. Firstly, if we change the K.V. by a small amount in the region of 50 K.V., $\rho\left(\frac{\mu}{e}\right)_{Al}$ will vary by a much larger amount than if the same change took place at a higher voltage (cf. Figure 6) Secondly, as the thickness of the scatterer is decreased $\rho\left(\frac{\mu}{e}\right)_{Al}$ is increased without change of voltage.   The thinner the scatterer the greater the change in $\rho\left(\frac{\mu}{e}\right)_{Al}$ for the same small change in scatterer thickness.

This type of investigation was then carried out on apparatus II using cpdc. to excite the tube.   The results shown in Figure 25 were obtained with the Siemen 234303 tube.   The scatterers
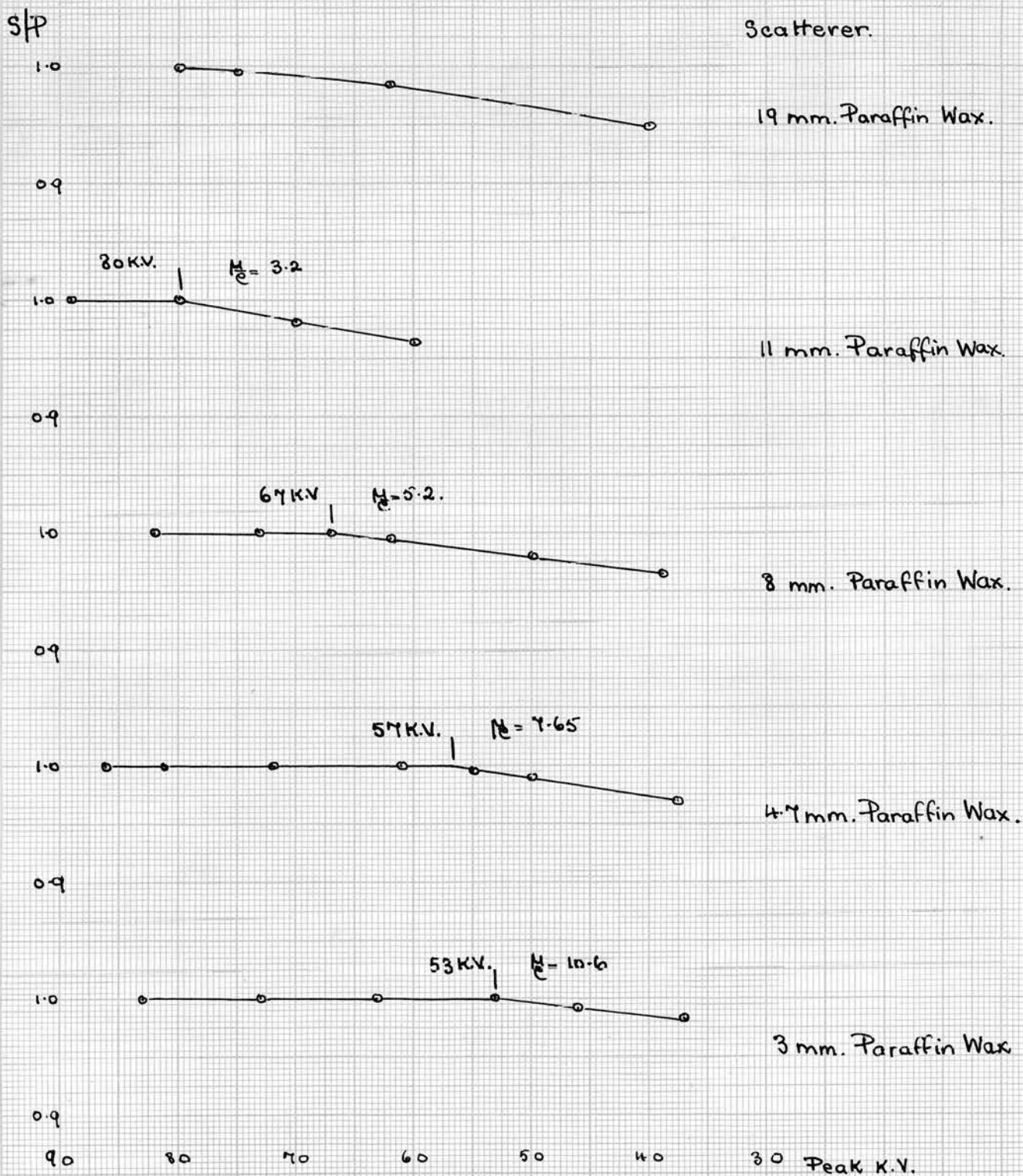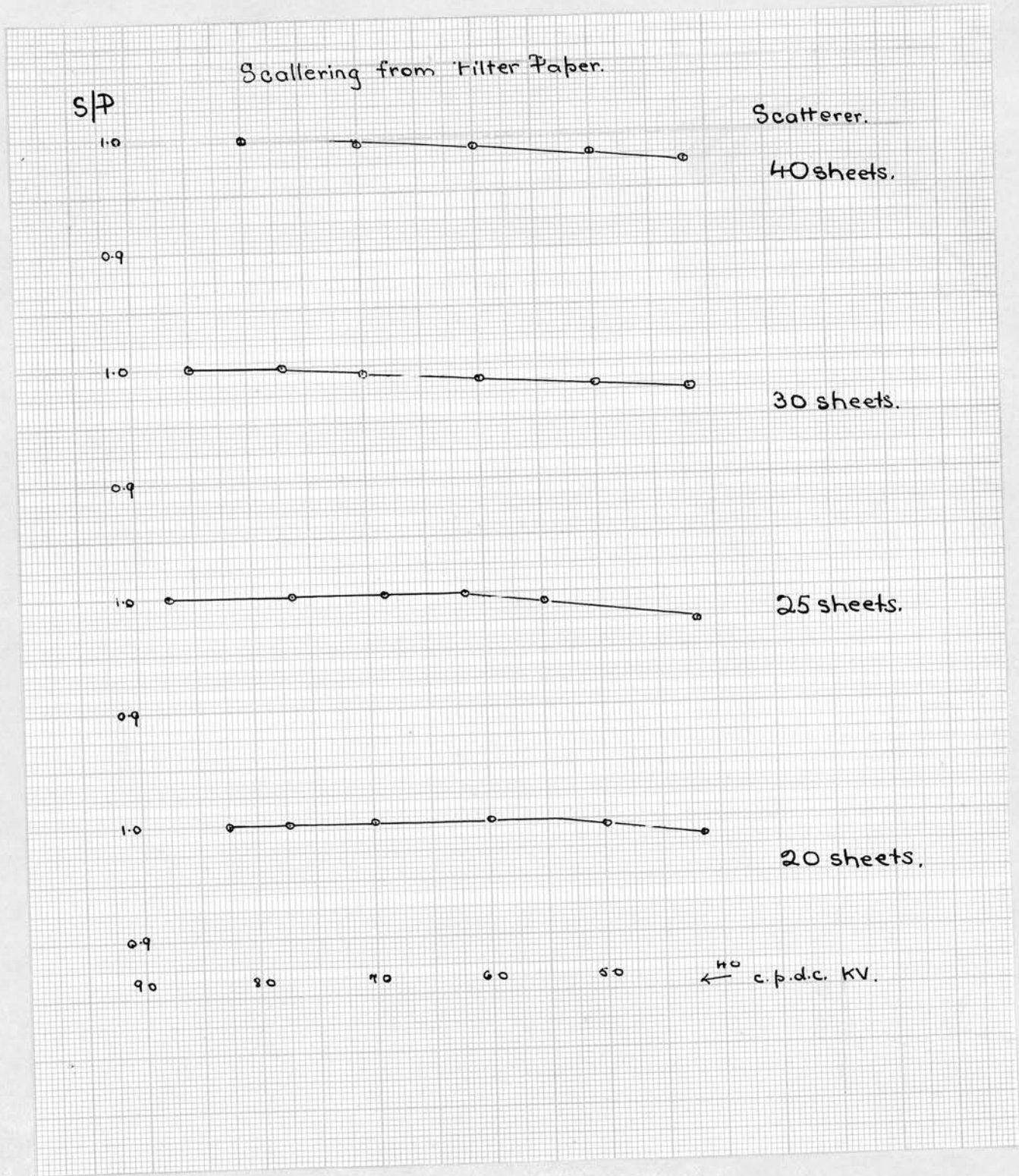
Figure 24

Figure 25

consisted of sheets of filter paper, of varying number;   the
primary aperture was of four holes each 0·6 mm. in diameter,
situated at the corners of a square of side 6·0 mm.   The gas
ionized was air.   The conclusions drawn from Figure 24 are com-
pletely verified.   As the scatterer thickness is decreased the
length of the horizontal portion is increased.   Thus both sets of
apparatus agree as to the effect of changing the thickness of the
scatterer and that this holds for both paraffin wax and filter paper
scatterers.   In one case the tube was excited by ac., and the gas
ionized SO_2, in the other, cpdc. excited the tube, and the gas
ionized was air.

The results given so far indicate that horizontal lines
are much more frequent than smooth curves.   This is due to the
selection of results to show how the horizontality is affected.
Frequently no horizontality appears at all.   Figure 26 makes an
interesting comparison with Figure 24.   In both cases results were
obtained on apparatus I with the Siemens VS 1400 tube, excited by the
ac. transformer.   But in Figure 24 when the 11 mm. and 8 mm.
scatterers were used horizontal lines were obtained.   But as we
see from Figure 26 these scatterers now produced smooth curves.
The factors causing these differences must have been introduced
by the primary aperture which was the only thing changed when the
second series was taken.   For the experiments recorded in Figure 24
the primary aperture was 0·6 mm. in diameter, for those recorded in
Figure 26 it was 1·0 mm. in diameter.   Thus the rule given above
connecting the horizontality of the S/F and voltage curve with the
thickness of the scatterer, holds for different sizes of primary
aperture, but the thickness of the scatterer for which this
horizontality just appears (or disappears) is seen to depend on the

size of this aperture.   The results given above are not isolated

cases, but typical results selected to illustrate the behaviour
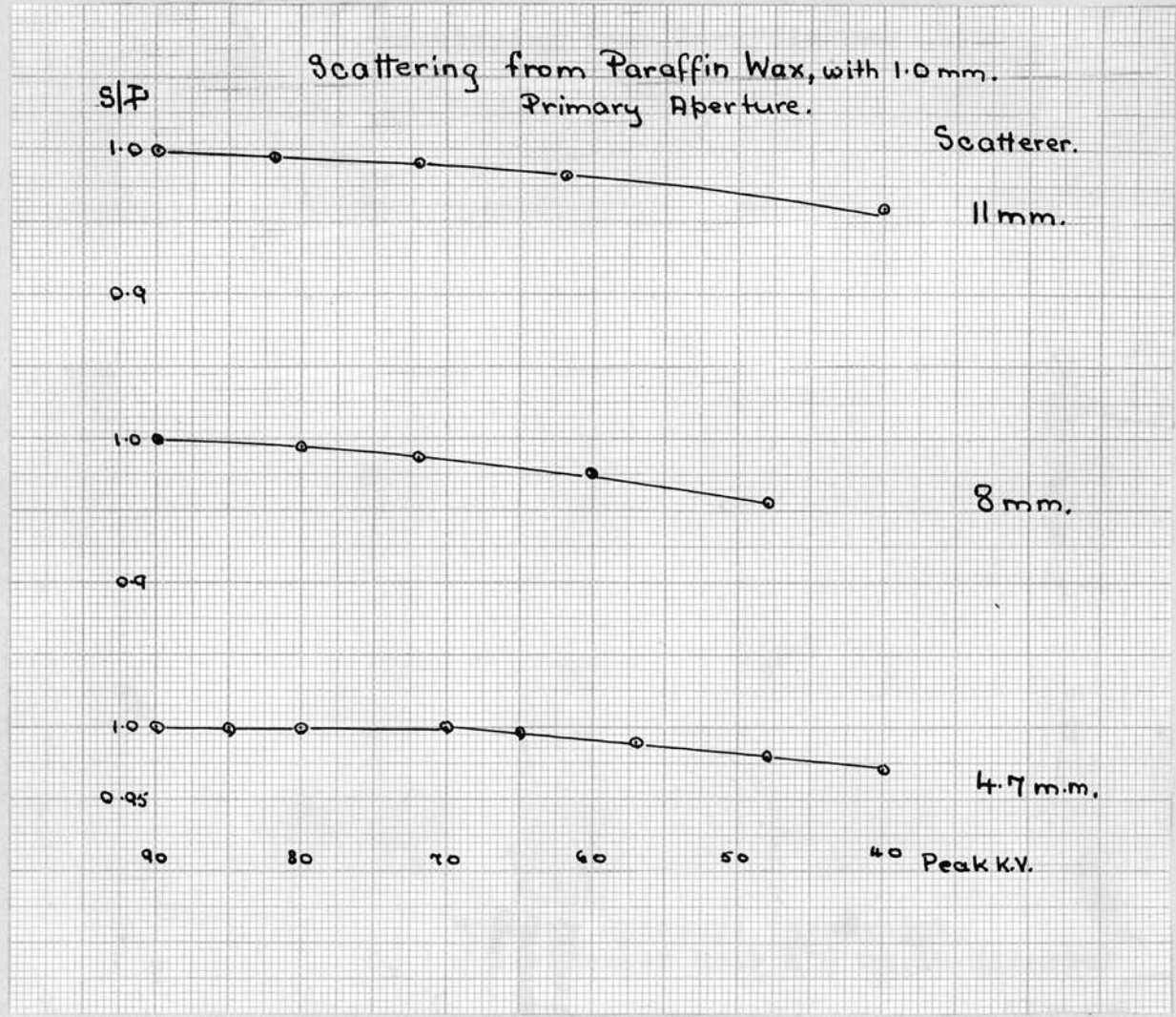
of the curves.

Figure 26

When the filtering experiment was discussed it was pointed

out how exceptions were caused by the use of a thin slit as primary

aperture.   Figure 27 shows exceptions are also found in the

scattering experiment when a fine slit is used as primary aperture.

These results were obtained on apparatus II with the tube Siemens

234303 when the primary aperture was a fine slit of dimensions 0.2

x 7 mm.   In all cases the value of S/P decreased for high voltages,

a result which is entirely new.   This was most marked for very
thin scatterers (3 mm.) and for thick (11 mm.)   The behaviour
at the soft end of the curves shows that the rule for the critical
voltage is obeyed i.e. at low voltages the results are normal,
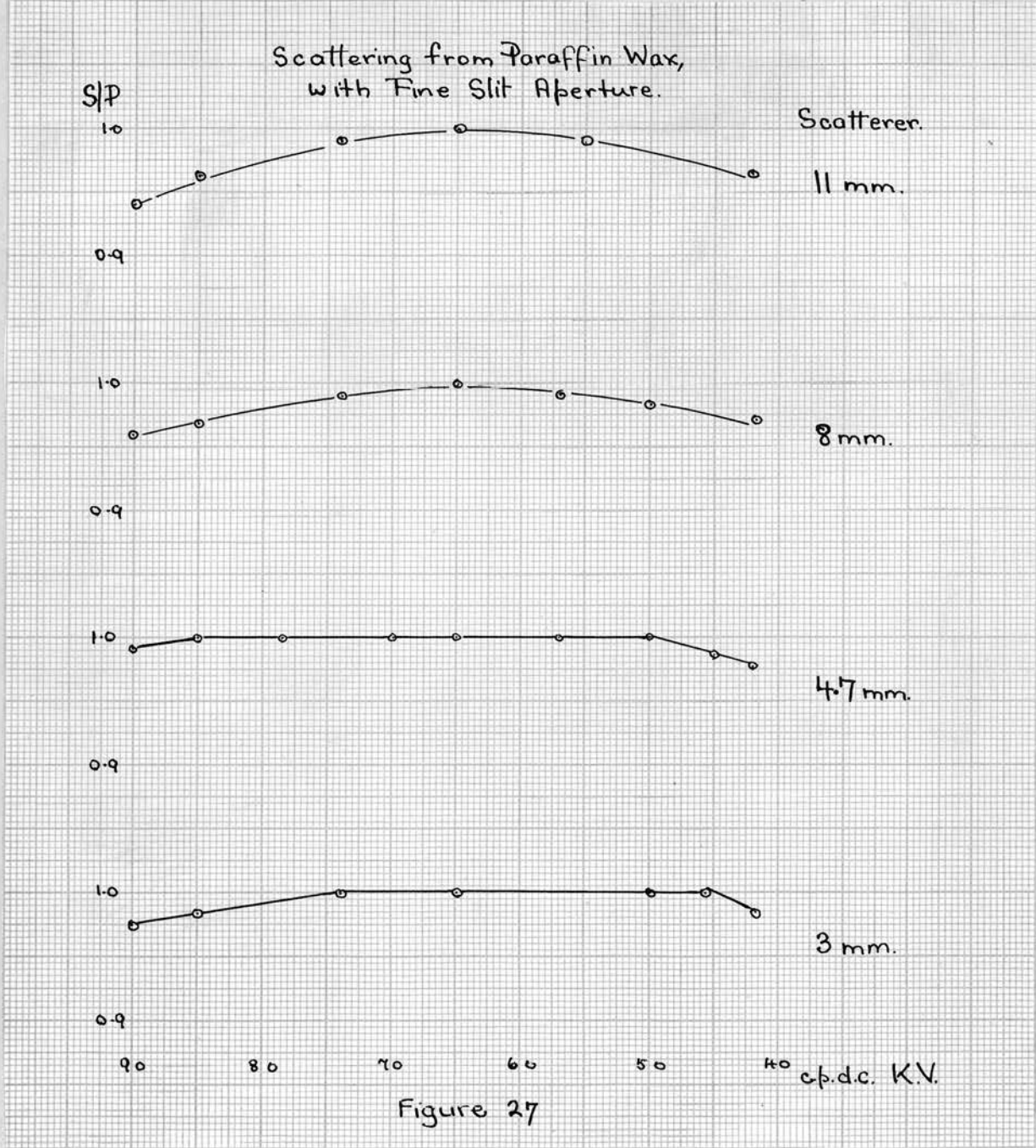

Figure 27

while at high voltages they introduce a new phenomenon, where either
S decreases or P increases in a manner unknown where wider primary
apertures are considered.   Shortly after performing this experiment

it was discovered that when the jaws of the slit were closed
radiation was still being received in the primary ionization
chamber, if the primary beam were very penetrating. Thus when the
slit was being used as an aperture the beam which was being measured
must have consisted of two parts, one which had come through the
opening and one which had come through the lead of the jaws. This
was 1·7 mm. thick. For low voltages the x-ray quanta did not have
sufficient energy to penetrate the jaws. This explains the drop
at the left - the penetrating end of the curve, as being due to the
increase in P when the radiation penetrated the jaws. Whether
this would account for the whole drop was a matter for experimental
verification. Further experiment showed that not more than 2% of
the radiation entering the primary chamber at 90 K.V. could have
come through the thin jaws of the slit. When this is applied to
Figure 27 we see that this explains the decrease at the penetrating
end for the curve with the 4·7 mm. scatterer, but cannot explain
the whole of the drop for the thinner scatterer, although it lessens
it. Subsequent experiments with a thick-jawed slit, showed that
at the penetrating end S/P decreased. Thus the slit does introduce
some other factor.

It is obvious from Figures 24 and 26 that the size of the
primary aperture affected the length of the horizontal portion of
the scattering curve. Considering the curves taken with 4·7 mm.
paraffin wax as scatterer, the critical voltage was 57 K.V. when the
aperture was 0·6 mm. in diameter and 70 K.V. when the aperture was
1·0 mm. in diameter. Each of these curves was determined
separately, on different days, but the position of the break-away
point on the earlier curve was found to be unchanged after obtaining

the other curve.   This procedure was frequently adopted, i.e.
obtaining results on separate days and verifying the earlier ones,
but occasionally the value of S/P at a given voltage was determined
with a certain primary aperture, and while a constant voltage was
maintained the primary aperture was altered and the new value of
S/P determined.   The initial aperture was then restored to check
any variation.   This was then repeated at another voltage.   This
method of approach proves that the change in result is due entirely
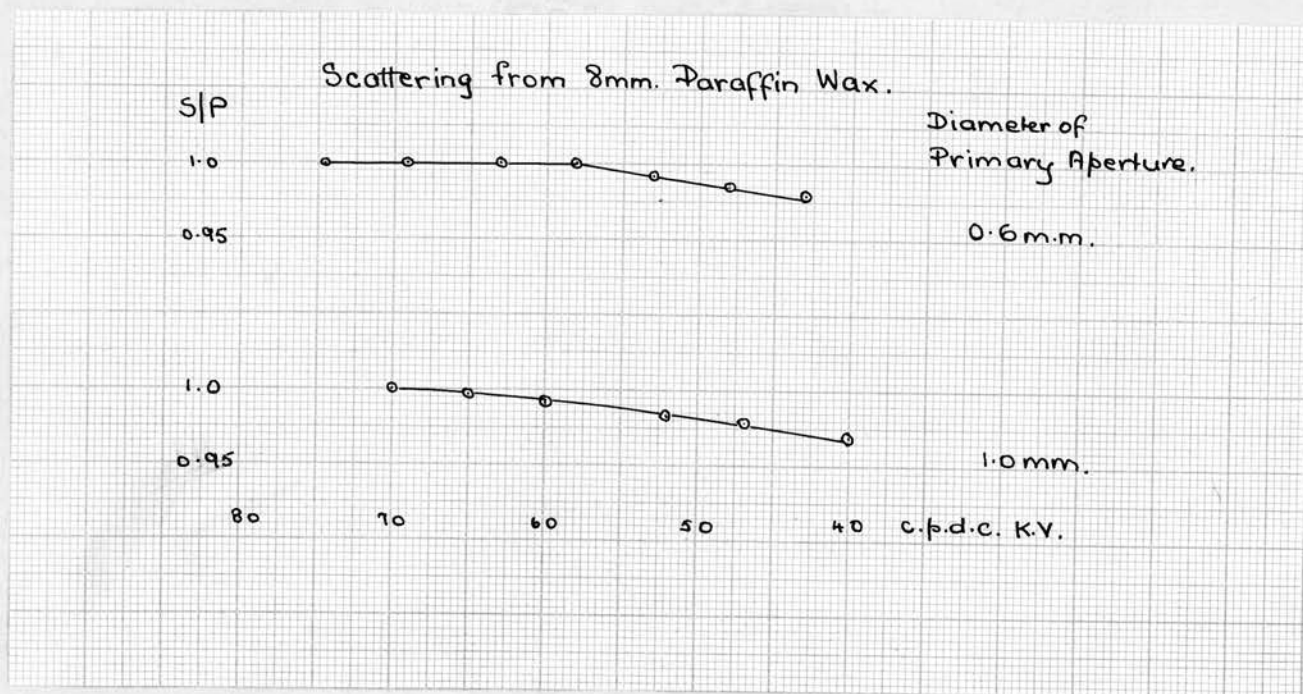to the change in aperture.

Figure 28

Figure 28 shows how a curve of the smooth type can be
tranformed into one of the horizontal line type merely by using a
smaller primary aperture.   These results were obtained on
apparatus II with a cpdc. source of high tension.   The gas ionized
was air; the tube employed Cuthbert Andrews 33983.   If a larger
aperture was used, say one of 1·5 mm. diameter the curve was still

of the smooth type, and differed very little from that with the
1·0 mm. aperture. There would thus appear to be no aperture
effect. It must be made clear that the change with aperture is
noticed, only when there is horizontality. As the aperture is
increased the horizontality tends to disappear, but after it has
disappeared, a further increase of the size of the aperture has
little or no effect on the shape of the curve.

One further point arose in connection with this change
with aperture, i.e. whether it was the total area of the aperture
which affected the result, or the dimensions of the individual holes.
If one aperture consisting of 4 holes each 0·6 mm. in diameter were
used would the result agree with that when one hole of 0·6 mm. is
used, or would it tend to agree with that for 1·0 mm. since the area
of the four holes would be only slightly greater than that of the
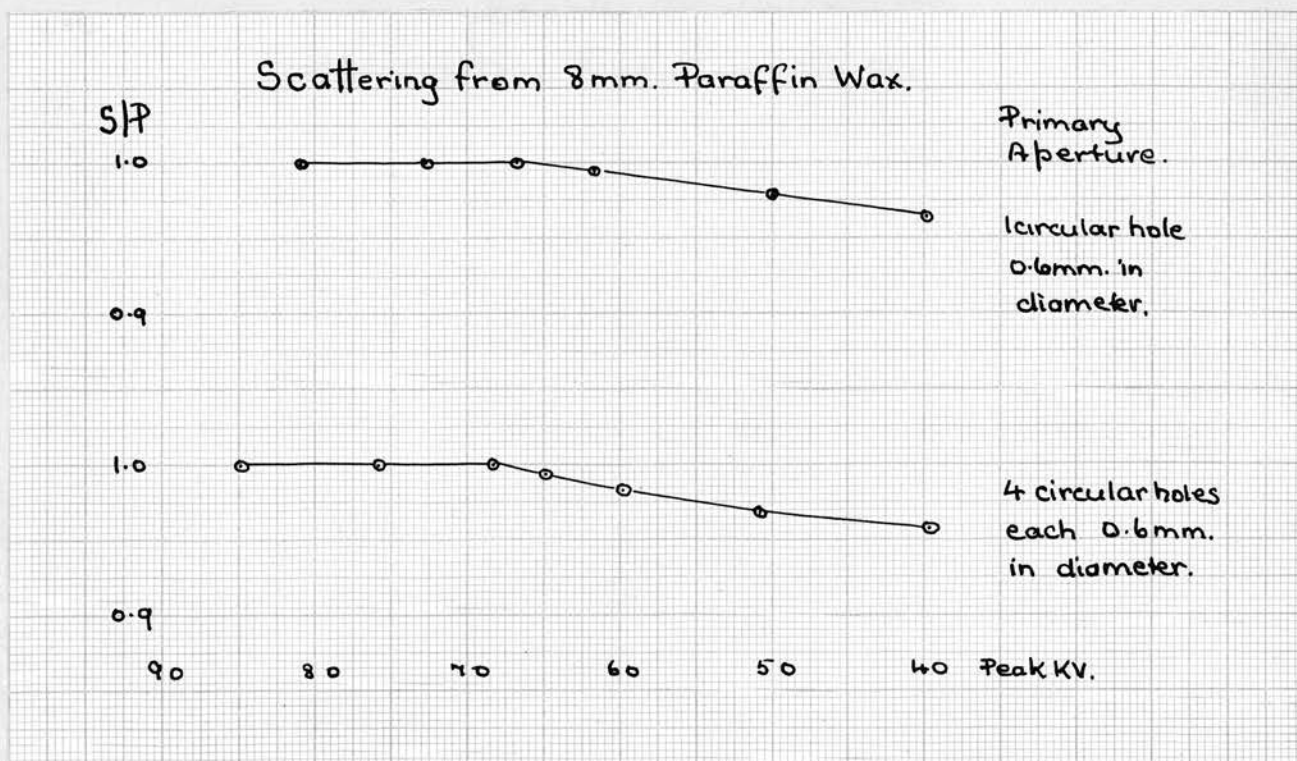1·0 mm. diameter hole?

Figure 29

In Figure 29 the results of such a comparison are shown. There is surprising agreement between the curves apart from a slight change in shape at the soft end. These curves were obtained on apparatus I with the Siemens VS1400 tube, excited by the ac. transformer, the gas ionized was SO_2. The result obtained when a 1·0 mm. aperture was used, was a smooth curve with no sign of horizontality. There can be no doubt that it is the dimensions of the individual holes that matter, not their total area. The holes in question were situated at the corners of a 6 mm. square.

The other apertures may be considered here. If the apertures which limit the incident beam are altered the patch of the scatterer which emits scattered rays is also altered, and this affects the intensity of the secondary beam. If we try to make the experimental conditions approximate to the theoretical, we should have to cut down the incident beam into a narrow cylinder. This would produce such a feeble secondary beam that the duration of readings would be impossibly long. Within limits, however, the apertures between the tube and the scatterer have been altered to vary the diameter of patch of radiation on the scatterer by approximately five-fold. No variation in the results could be detected. This also applies to the apertures limiting the secondary beam. These apertures, it must be noted, are all very much larger (being of the order of 2·0 cm. diameter) than the primary apertures which have been found to influence the results (0·6 mm. and 1·0 mm. in diameter).

The effect of the type of x-ray tube on the results was also the object of experiment. There are marked differences between the radiation supplied by, say, a Philips Metalix tube and

a Coolidge tube.   Not all the work described in the previous pages
has been done with one tube.   It is therefore obvious that the
phenomena are not confined to any one tube, but the scale on
                      might
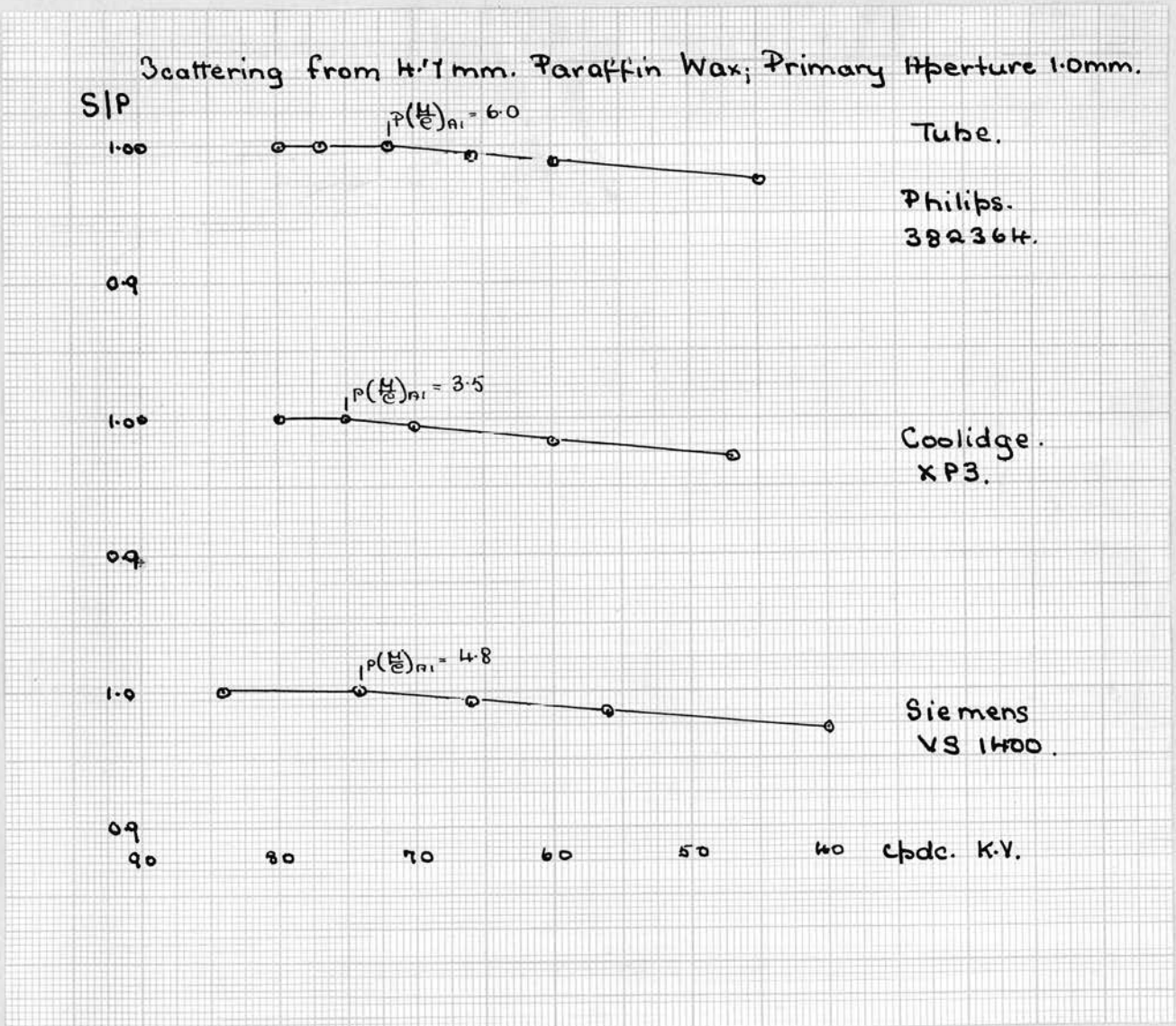which they occur ~~may~~ vary with the tube.

Figure 30

Figure 30 records the result of one experiment performed
with three different tubes, Philips 382364, Coolidge XP3, Siemens
VS1400.   The experiment consisted of scattering from 4·7 mm.
paraffin wax using a single hole of 1·0 mm. diameter as primary

aperture.   The gas ionized was air.   The experiment was carried
out on apparatus II.   The voltage above which the scattering curve
is horizontal is the same in each case (within the limits of error),
although the values of mass-absorption coefficient of the primary
beam are widely different.   Obviously the result is the same for
all these tubes.   This result is typical of many experiments
performed on apparatus I and II in which no affect could be traced
to the tube.

The difference between the output of various tubes of
given anti-cathode material is presumably due to the various filter-
ing powers of the windows.   Thus it should be possible to make the
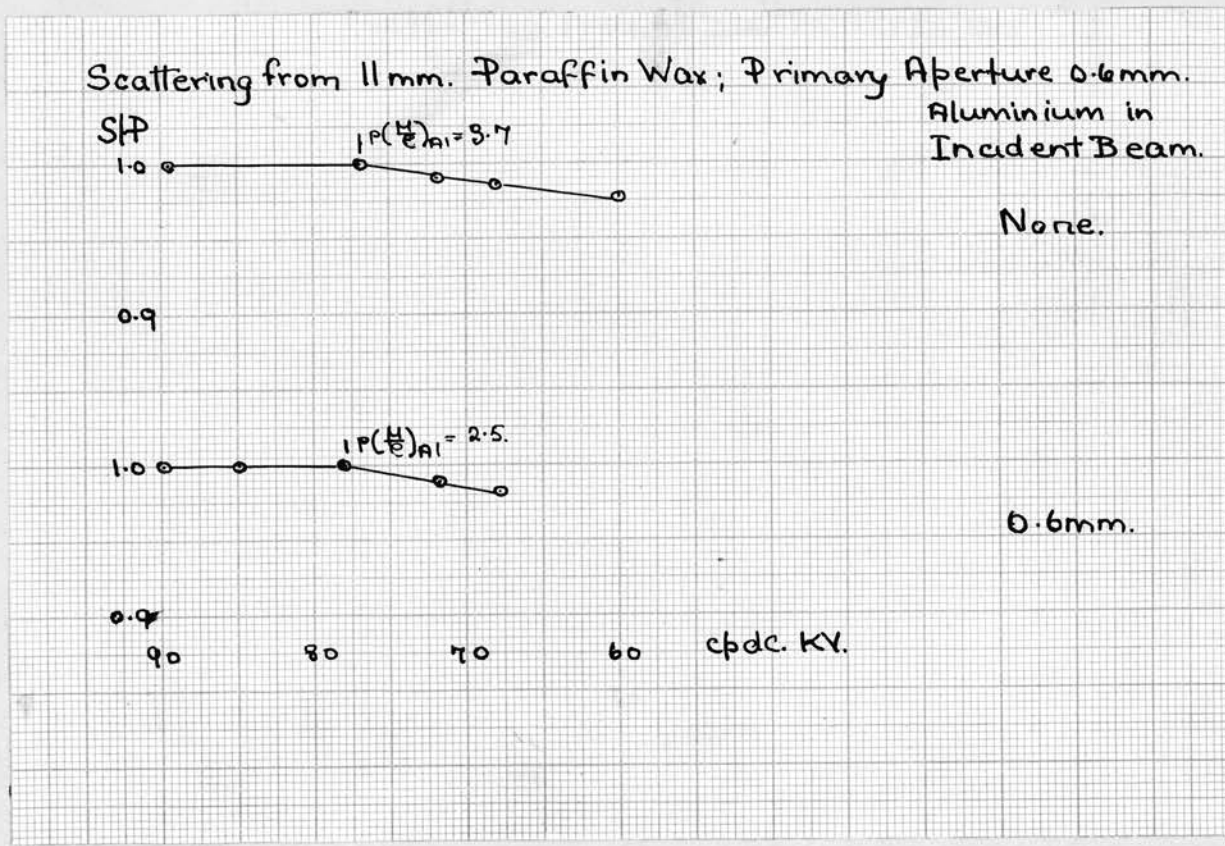
Tube: Philips Metalix 382364.   Primary Aperture: 0·6 mm.
        in diameter.   Apparatus II.

Figure 31

output of two tubes equal by adjusting the thickness of aluminium in the incident beams of the tubes. Since two tubes of different output gave similar experimental results, we expected that there would be no difference in result between two scatterering experiments conducted with a given tube, one having no aluminium between the tube and scatterer, the other having a constant thickness of aluminium to filter the beam falling on the scatterer, all other conditions remaining constant. This supposition was confirmed when scattering curves were obtained on apparatus II with Philips 382364 tube which supplied a very soft radiation. Figure 31 shows that when scattering curves were obtained from 11 mm. wax with a 0·6 mm. hole as primary aperture, the curve was unchanged when 0·6 mm. of aluminium were inserted in the primary beam. More aluminium might cause an alteration in the shape, but the point of the experiment was only to modify the beam sufficiently to make it comparable with that from another tube. This result has been confirmed under other conditions and explains why different tubes give similar results in the scattering experiment.

It will be well to summarise briefly here the results of these experiments as recorded on apparatus I and II.

(1) The graphical result of the scattering experiment when S/P is plotted against kilo-voltage consists either of a smooth curve concave downwards, or of a curve with a horizontal portion at the high voltage end, which disappears at a certain kilo-voltage. At lower voltages the curve may be a straight line of negative slope, and may depart slightly therefrom, if the latter the curve is concave upwards.

(2) The factors which influence the shape of the curve are

    (a) Thickness of scatterer.

    (b) Size of the Hole(s) of the primary aperture.

(3) The others factors mentioned on page 51 have been found to be without influence on the result.

(4) (a) The influence of the scatterer has been found to be as follows - if horizontality is not present it can usually be produced by decreasing the thickness of the scatterer.   Once horizontality has been produced, it can be extended to lower and lower voltages by further decreasing the thickness of the scatterer.

(b) The influence of the aperture is more complicated: the smaller the size of the individual holes, the greater the chance of horizontality (unless the scatterer is very thick).   Once horizontality has been produced it can be extended to lower and lower voltages by decreasing the size of the hole(s) of the aperture.   However when a very fine aperture is present results are found in agreement with the above, at low voltages but not at high voltages.

(5) The deductions from experiments on apparatus I and II are in complete agreement.   The scale on which the phenomena occur is the same for both sets of apparatus.

Some scattering experiments were performed on apparatus III.   These will be discussed more fully in the next section.   The broken lines of Figures 39, 40 and 41, give the relationship between S/P and the kilo-voltage values for given combination of conditions. These show the completely different character of the results from

apparatus III.   Horizontality is much more extensive and appears
under conditions of thickness of scatterer and size of aperture
where no horizontality would show on apparatus I and II.

It has already been mentioned that several of the workers
in this laboratory have found the shape of a given curve to vary,
i.e. seemingly identical conditions would not produce identical
results.   This phenomenon occurred when the writer was in collabora-
tion with Mr.Stevens to determine scattering curves on apparatus III,
but was not found on apparatus I or II.   This made the results
obtained on apparatus III difficult to classify.   Generally speak-
ing the influence of the thickness of the scatterer is the same as
on apparatus I or II.   The aperture effect is also as stated above,
though this is less certain.   A very wide aperture may produce
horizontality at the lowest voltage we can employ.   Therefore we
cannot say the precise nature of the differences produced by a
smaller aperture.

At this point it is possible only to state that while the
general conclusions to be deduced from the different apparatus are
the same, the scale on which the phenomena are recorded on
apparatus III is different from that on either apparatus I or II.

SCATTERING   EXPERIMENT   (SECTION B).

The results of the scattering experiments discussed above
have been obtained by altering the voltage on the tube and thus
altering the penetrating power of the radiation.   It is of course
possible to alter the penetrating power otherwise, and in the
experiments described below when the ratio S/P is plotted against
$P\left(\frac{\mu}{e}\right)_{Al}$, the latter may have been altered by voltage changes only,
or by inserting sheets of aluminium between the tube and the
scatterer.   It is thus possible to obtain any given value of $P\left(\frac{\mu}{e}\right)_{Al}$
in various ways according to the arrangement of voltage and alumin-
ium hardening the incident radiation.   Similarly for a given kilo-
voltage the value of $P\left(\frac{\mu}{e}\right)_{Al}$ depends on the thickness of aluminium
inserted.   Thus for every point on the graph two quantities;   the
kilo-voltage on the tube and the amount of aluminium in the incident
beam, have to be specified, as well as the ratio S/P and the value
of the mass-absorption coefficient.   Unless it can be shown that
all beams of given voltage affect the electroscope in the same way,
whatever their penetrating power, or that all beams of one penetrat-
ing power are equivalent, these two quantities (kilo-voltage and
thickness of aluminium) must be stated in these experiments in which
both are altered.

The first experiments of this series were performed on
apparatus I when the tube was excited by the ac. transformer.   The
scatterer was 19 mm. Paraffin Wax and the primary aperture 1·5 mm.
in diameter.   When the voltage only was changed the scattering
curve showed no horizontality.

The result of such an investigation is given in Figure 32.

The first curve of the figure was obtained by using the Coolidge

Tube 43712, which had a molybdenum-anticathode.   The dotted lines
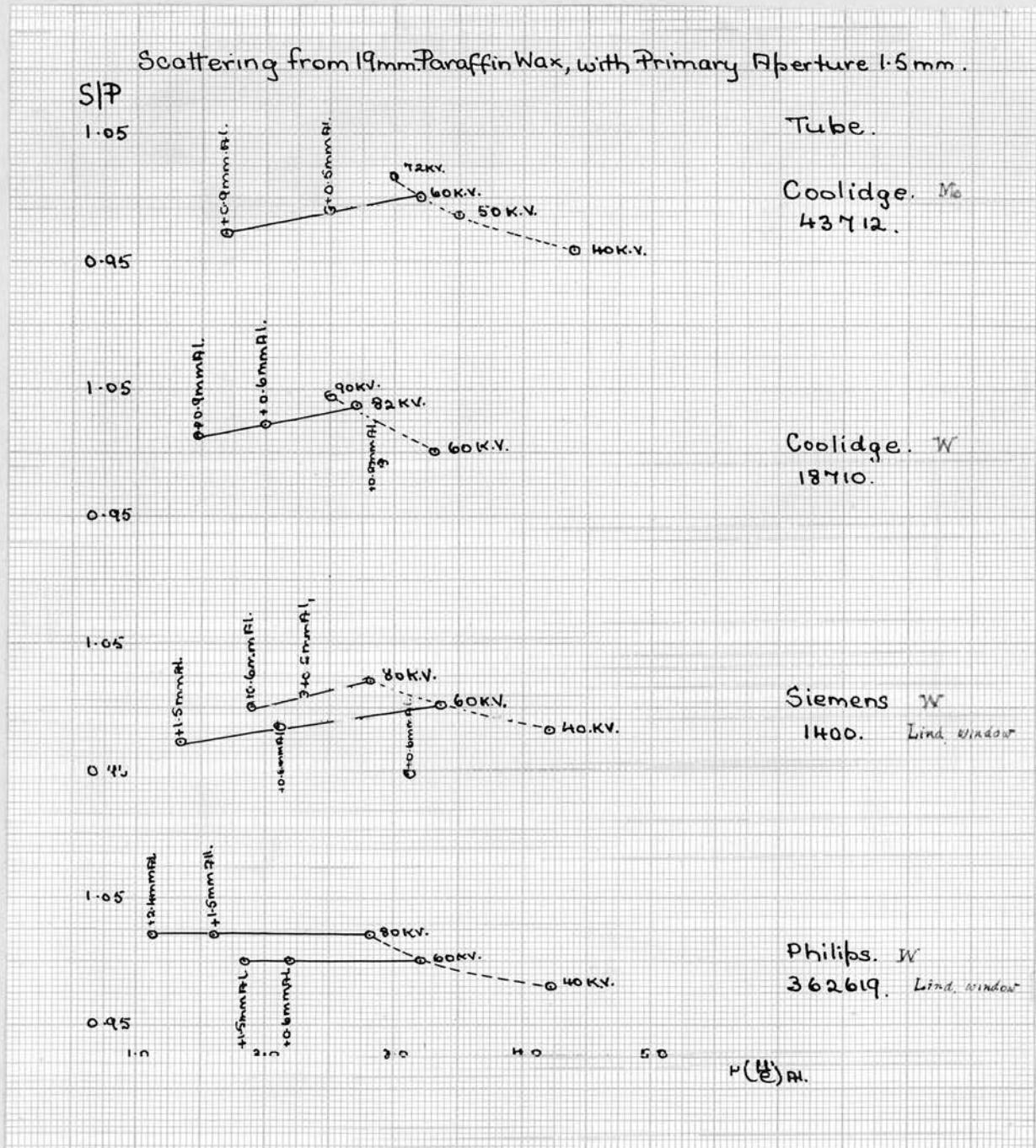

Figure 32

on the figure join points for which the thickness of hardening

aluminium is constant.   This of course includes the case in which

no aluminium was used, as in the experiment under discussion.   The

points joined by a continuous line represent readings taken at the
same voltage but with varying amounts of aluminium to harden the
incident beam.   As can be seen from the figure when the softer
rays are filtered out at 60 kilo-volts the ratio S/P decreases with
decreasing $P\left(\frac{\mu}{e}\right)_{Al}$.   Thus hardening the beam by filtering out
the soft rays has a markedly different effect from hardening it by
raising the kilo-voltage.   In the latter case S/P increases with
decreasing $P\left(\frac{\mu}{e}\right)_{Al}$.   Also from this curve we see that there is no
unique value of S/P for one given value of $P\left(\frac{\mu}{e}\right)_{Al}$, and likewise
S/P may have an infinite number of values for a given kilo-voltage.
Thus we must always specify both the kilo-voltage and the thickness
of aluminium.

The second curve in the same figure shows a repetition of
this experiment done by the Coolidge 18710 tube which had a tungsten
anticathode.   This was done to determine the effect (if any) of the
material of the anticathode.   The same type of results appears
once more; an increase of voltage only, gives an increase in S/P;
an increase of thickness of hardening aluminium at constant voltage
gives a decrease of S/P.   This is shown for 60 kilo-volts. and 82
kilo-volts.   Both these tubes were of the old Coolidge type where
the rays had to penetrate the glass of the walls of the tube, no
special window being provided.   Thus the radiation from these
tubes was harder than that from a tube with a Lindemann window, e.g.
the Siemens VS 1400.   But since these tubes, Coolidge 18710, and
Siemens VS 1400 both had tungsten anticathodes, their radiations must
have differed only in penetrating power.   If sufficient aluminium
is inserted in the incident beam from the Siemens tube to compensate
for the difference in the windows, the beams should be similar.

Experiments therefore done by these tubes should lead to similar results especially in the case in which a thick scatterer is used, as this filters out soft rays. This reasoning suggests that all tubes with a tungsten anticathode would give similar results.

The third curve in this figure when compared with the second bears out this suggestion. The right hand broken line was obtained when no aluminium was in the beam. The other broken line was obtained when 0·6 mm. of Al were in the beam, at various voltages. This result shows that as the voltage is altered, the shape of the curve is much the same whether aluminium is present or not, (provided of course the thickness of aluminium is unchanged during the readings).

The fourth curve of this series was obtained by the Philips Metalix tube 362619, which had a Lindemann window. This tube gave a very different result. For 80 kilo-volts there is only one value of S/P no matter how much aluminium is in the beam, or what the value of mass-absorption coefficient. The same is true for 60 kilo-volts. This horizontal portion does not seem to be part of a line of small slope. The variations in S/P are slight and entirely random over the range investigated; they are all within the experimental error. This well-marked horizontality calls for further investigation.

Firstly the effect of the thickness of the scatterer was examined. The arrangement of apparatus was kept unchanged, apart from the substitution of an 11 mm. scatterer for the 19 mm. one.

As can be seen from Figure 33 the horizontality disappears when a thinner scatterer is used. This is in marked contrast to the horizontality produced by voltage change only, which is greatest for thin scatterers, and indeed does not appear at all for 19 mm.Wax.

Also the voltage produced horizontality is independent of the tube (p. 62) whereas the tube is important in this horizontality produced by filtering out the softer rays.
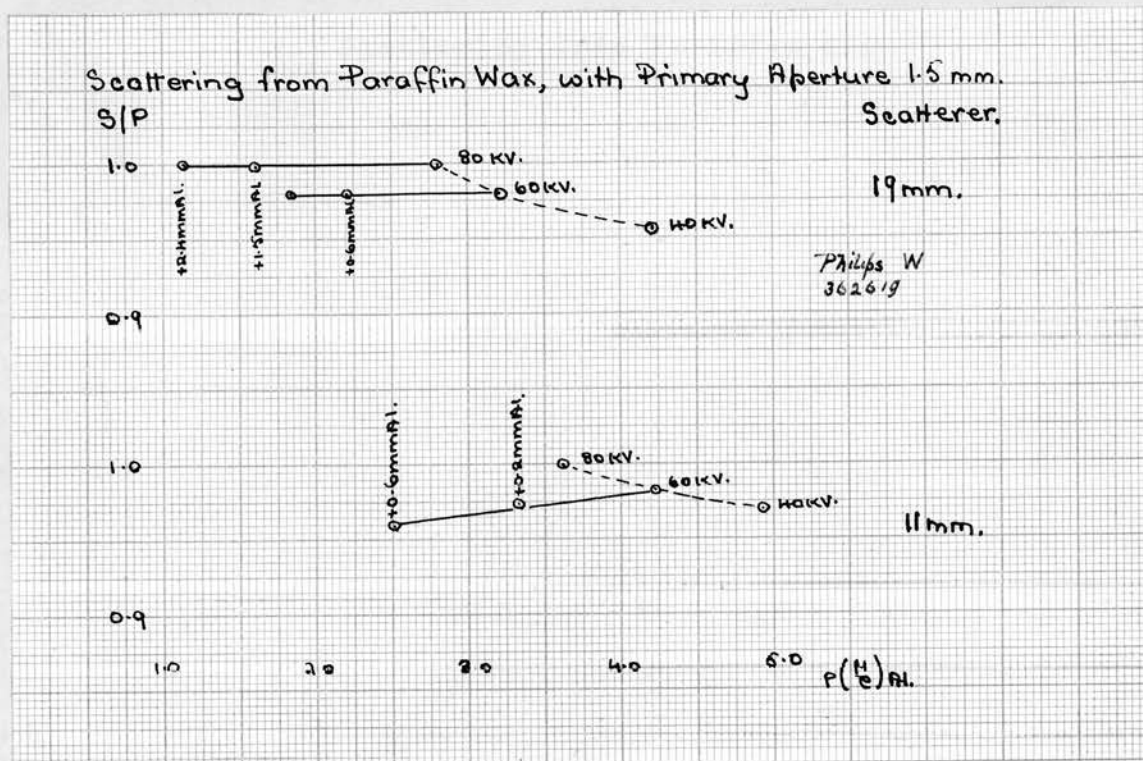
Figure 33

Now different tubes produce beams of differing energy-wave-length distribution, owing to the different filtering powers of the windows.   But the same tube can be made to produce beams of differing energy wave-length distribution by varying the mode of excitation.   Normally the tube in apparatus I was excited by an ac. transformer, but leads from the cpdc. apparatus could be connected to it.   This was done in order to investigate the effect of alteration of the constitution of the beam.   A given steady cpdc.voltage produces a harder beam than the same (peak) ac. voltage, as during most of the cycle the voltage on the tube is very much less than the peak value.   The experiment with 19 mm. Paraffin Wax as scatterer

was repeated with the cpdc. apparatus exciting the Philips Tube.
It was found that for a given value of kilo-voltage there was one
definite value of S/P, whatever the value of $_P(\frac{\mu}{e})_{Al}$. Thus whatever
change is produced in the beam by altering the mode of excitation,
that change is such that the factors producing horizontality are
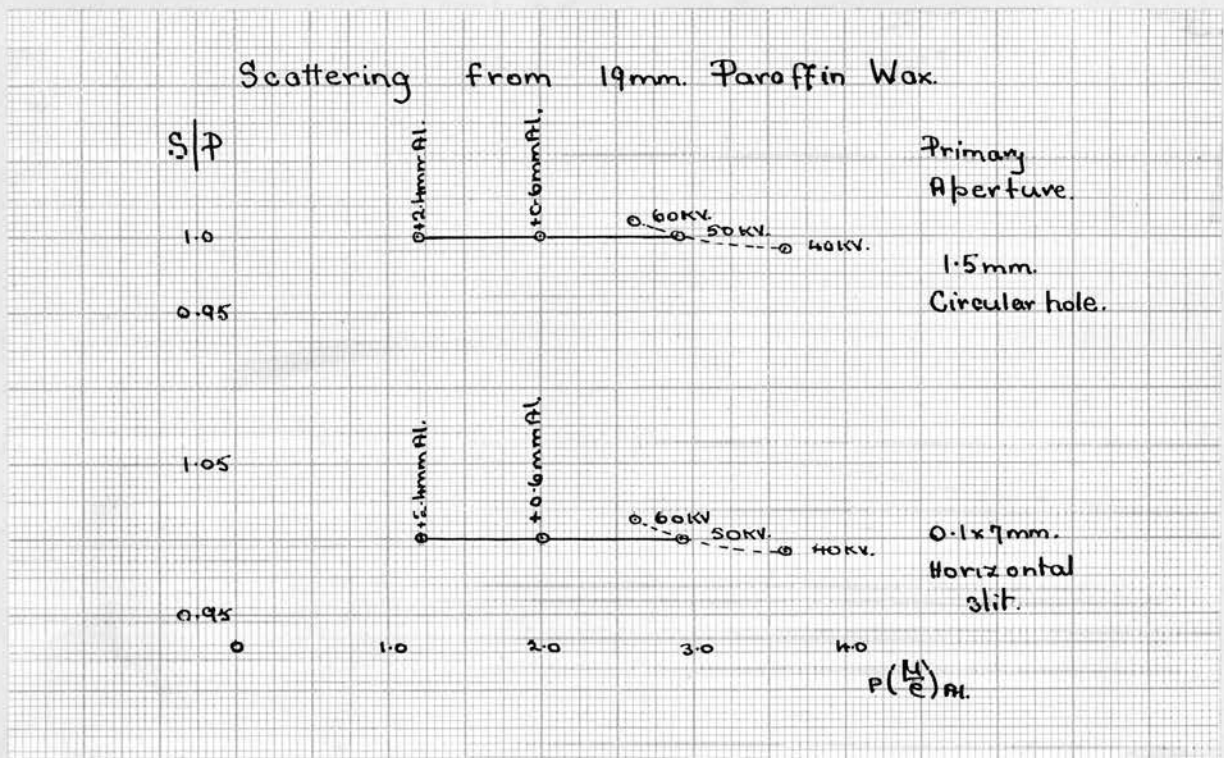unaffected.

Figure 34

All the experiments just described have been performed on
apparatus I. It was considered possible that the arrangement of
the apparatus, especially the measuring instruments might have some
effect upon the results. The Philips 362619 tube was therefore
transferred to apparatus II, with the 19 mm. scatterer and the 1·5 mm.
primary aperture. The other apertures were not interchangeable but
were replaced by ones of approximately the same size. The upper of
the curves in Figure 34 shows the result of this experiment on

apparatus II.   The horizontality is unchanged by the change of
apparatus.   This confirms what was noted before (p. 66)   that
the results given by apparatus I and II are in agreement.   This
curve was obtained when the cpdc. apparatus supplied the high tension.
The agreement between results from both apparatus I and II is inter-
esting in view of the fact that on apparatus I the gas ionised was
SO_2 whereas on apparatus II it was air.   In both cases the tube
currents were of the order of 1 m.amp.

The investigation into the factors influencing this hori-
zontality was continued with apparatus II.   In other types of
experiment the size of the individual holes of the primary aperture
influenced the result to a marked extent.   The experiments just
described were performed with a single circular hole of radius 1·5 mm.
as primary aperture.   This was now replaced by a fine horizontal
slit 0·1 x 7 mm.   The lower curve on Figure 34 shows how the hori-
zontality produced on filtering out the softer rays at a given kilo-
voltage is independent of the primary aperture;   a result which is
markedly different from our previous experience on the voltage pro-
duced horizontality, on apparatus I or II.

In this connection i.e. influence of sizes of apertures
on the shape of the curve, two series of experiments were conducted
(a) altering the sizes of the apertures between the tube and the
scatterer and (b) altering the sizes of the apertures between the
scatterer and the secondary measuring apparatus.   In neither series
could any influence of these apertures on the results be detected.
It is worth noting that the alteration of these apertures alters the
energy-wave length distribution of rays entering the secondary
chamber, and yet this alteration still produces horizontality.   This

is unexpected since we have seen that the energy-wave-length distribution of the radiation is an important factor in these experiments.   In this case the energy-wave-length distribution of rays entering the primary electroscope is little changed by the limitation of the beam, but the rays entering the secondary electroscope must have been changed very markedly.   These conclusions (a) That the cross-section of the primary beam when it reaches the scatterer is without influence and (b) that the cross-section of the secondary beam when it enters the ionisation chamber is without influence on the result, have been verified on other occasions. These agree with the results of experiments on the filtering curves and the horizontal lines produced by voltage-change only.

The experiments described above in this section have been performed with thick scatterers and wide apertures.   The change of voltage alone does not produce horizontality in the scattering curve. In the experiments to be described, thin scatterers and small apertures were used in order to produce horizontality in the scattering curve.   When a high voltage excited the tube aluminium was inserted to harden the incident beam.   The variation of S/P with

$p\left(\frac{\mu}{e}\right)_{Al}$ is shown in the following figures.   As before the scattering curve obtained with voltage-change alone is shown by a broken line while that obtained by filtering out the soft rays with aluminium is shown by a full line.

Figure 35 shows the result of an experiment performed on apparatus I when the Siemens VS 1400 tube was excited by the ac. transformer.   As the scatterer was only 3 mm. of paraffin wax the primary radiation was very soft.   The primary aperture was a single hole 0·6 mm. in diameter.   As can be seen the scattering curve is of

the usual type, with S/P constant above a certain kilo-voltage, in this case 54 kilo-volts.   Below this point the curve has a negative slope.   The ratio drops with the insertion of aluminium at a high kilo-voltage, and drops more rapidly as a greater thickness is inserted.   Briefly then, when soft rays are removed from the beam the value of S/P decreases.
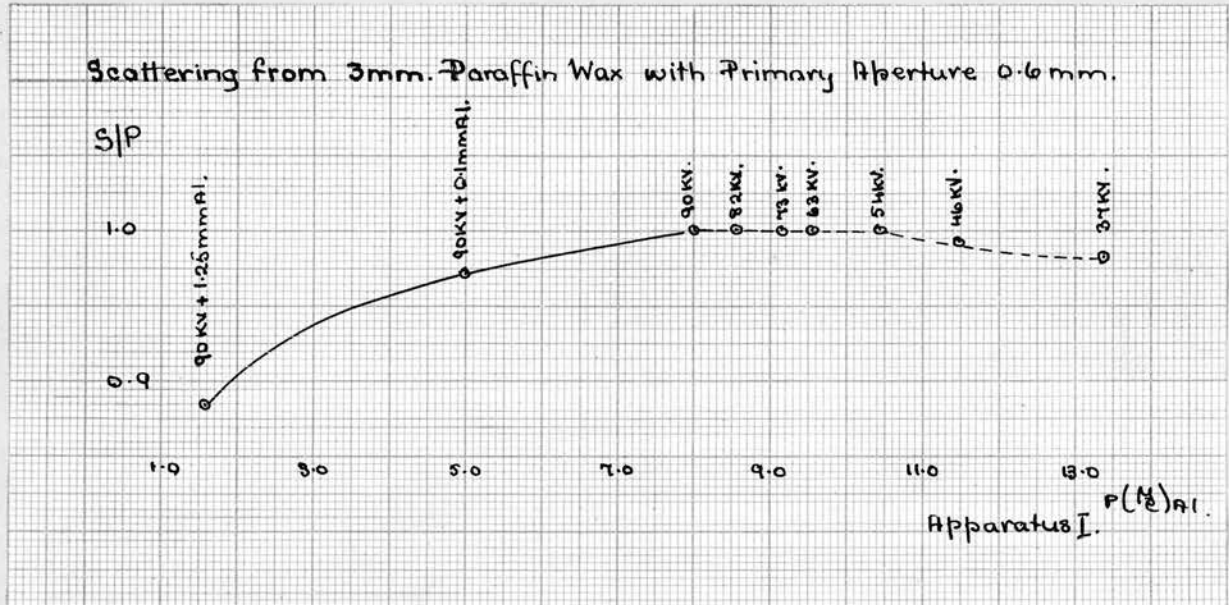

Figure 35

A similar experiment was carried out on apparatus II with the Philips 382364 tube operated on by the cpdc. apparatus. The scatterer was 2 mm. of paraffin wax, and the primary aperture 0·6 mm. in diameter.   The experimental result is shown in Figure 36. By a comparison with Figure 35 it can be seen that $p\left(\frac{\mu}{e}\right)_{Al} = 8\cdot0$ for 90 kilo-volts in both cases.   Once again the insertion of aluminium produces a decrease in the value of S/P, although the percentage drop in S/P over the same range of mass-absorption-co-efficient is not the same in both cases.   The difference in the left-hand sides of these two curves is the more remarkable when the similarity between the right-hand sides is noted.   This difference

may well be due to the difference in the tubes.   In the radiation
supplied by the Philips tube there are factors tending to maintain
S/P constant even on removal of soft rays as the experiments with
thick scatterers show.   These may well tend to horizontality in
this case too.

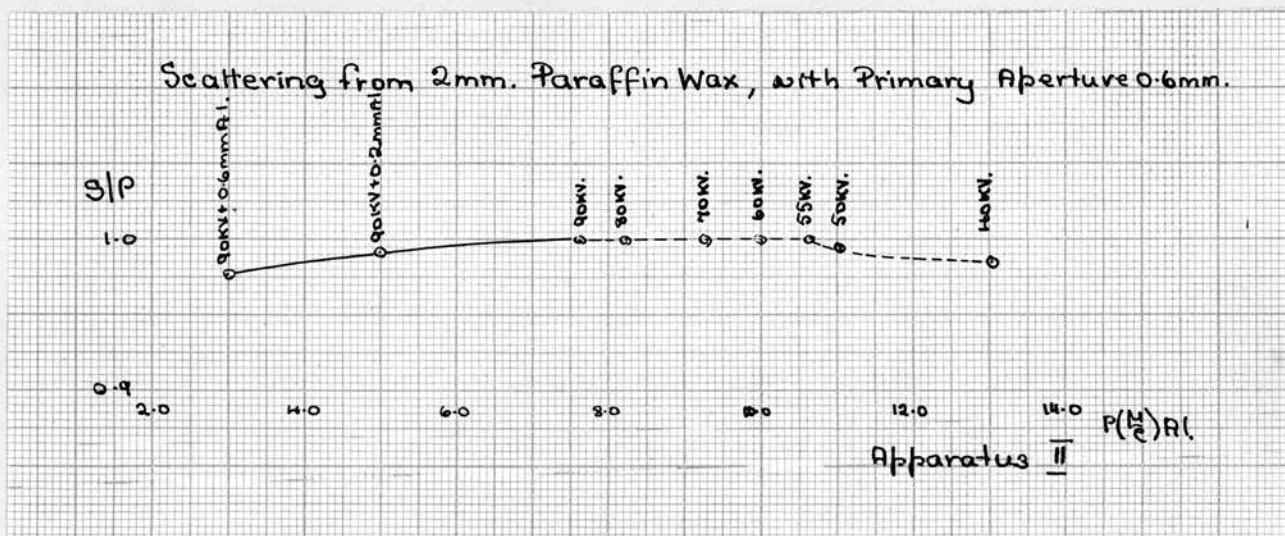Scattering from 2mm. Paraffin Wax, with Primary Aperture 0·6mm.

Figure 36

A harder primary radiation was supplied by the Coolidge
XP3 tube on apparatus II with a 4.7 mm. paraffin wax scatterer and a
primary aperture of 1·0 mm. in diameter.   The ratio S/P increased
with voltage to 75 kilo-volts.   From that point to 90 kilo-volts
the value was constant.   When aluminium was inserted the ratio
dropped.   From Figures 36 and 37 we see that 0·2 mm. aluminium in
the incident beam lowers the value of S/P by 1%, in both cases, and
0·6 mm.Al lowers the value by approximately 2·5%.   Owing to the
greater change in mass-absorption coefficient with the softer beam
the slope of the curve as thus drawn is less in the softer than the
harder case.   These curves shown are typical of many others obtained

on the apparatus I and II.   When aluminium is inserted between the
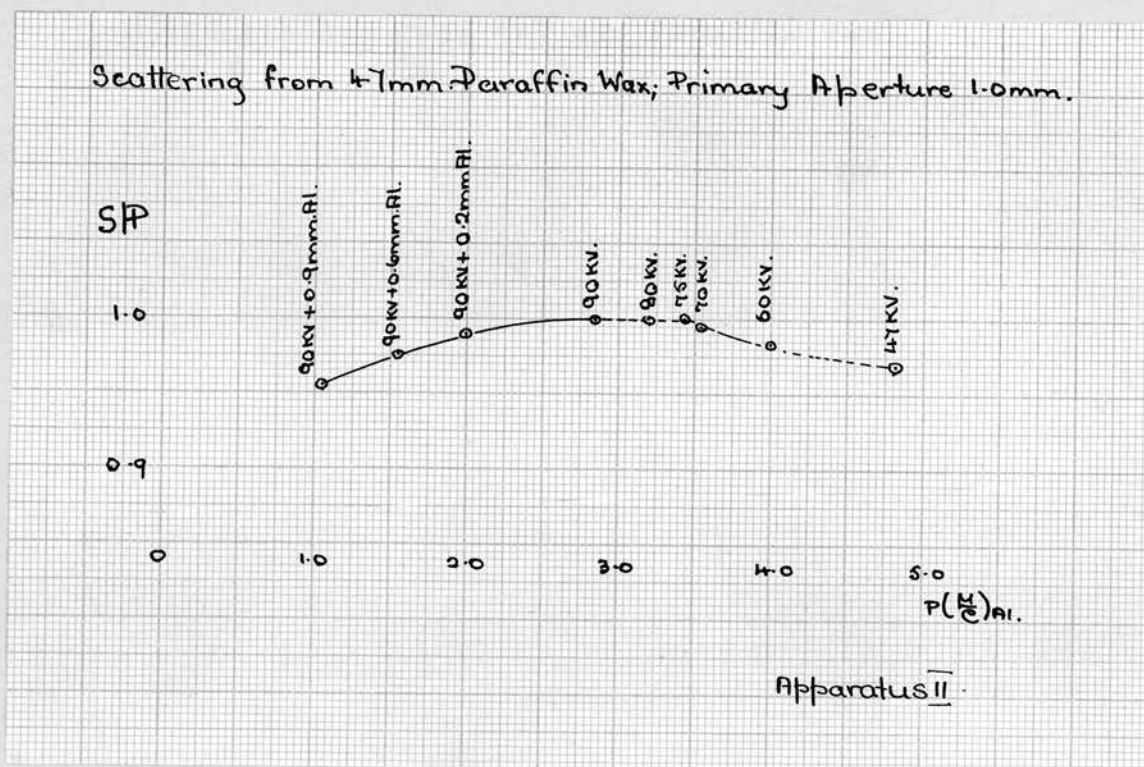

Figure 37

scatterer and the tube the ratio decreases, no matter how thin the
aluminium.   This refers to experiments where change of voltage only
produces horizontality at high voltage values.

Results have been described above of experiments performed
on apparatus I and II.   It has been seen that conclusions drawn
from experiments on one apparatus are in general valid for the other,
in spite of the difference in methods of excitation of the tube, i.e.
ac. transformers and cpdc. apparatus.   But the results obtained on
apparatus III are not in agreement with these.   The accuracy of
results on this apparatus is at least as high as on the other two.

For some years this apparatus has been used by Mr. Stevens in this laboratory. Owing to the seeming discrepancy mentioned above it was decided that he and the author should work in collaboration on apparatus III to determine what was the cause of the apparent discrepancy. Either an ac. transformer of the type mentioned on p. 20   or a cpdc apparatus consisting of two sections each one equivalent to that described on p. 22   could be used to excite the tube.

The first series of experiments was performed with wide apertures and thick scatterers. The results are shown graphically in Figure 38. The top curve is the result of an experiment performed with the Coolidge Tube 43712, excited by the cpdc. apparatus, when 19 mm. of paraffin wax were used as scatterer and the primary aperture was 1·5 mm. in diameter. The result of filtering out the soft rays at 80 kilo-volts is to produce a constant value of S/P.

The same experiment was repeated using the ac. transformer to excite the tube. The second curve of this figure gives the result, that the method of excitation produces no effect on the shape of the scattering curve, i.e. if when the tube is excited by a dc. source of high tension S/P is unchanged by filtering out soft rays, it will also be unchanged by the same operation when the tube is excited by an ac. source of high tension. This conclusion is therefore valid for both apparatus I and III. But the curves obtained by the Coolidge tube 43712 on apparatus III could not be obtained with this tube on apparatus I. Figure 32 shows in the top curve that S/P decreases when soft rays are filtered from the beam on apparatus I, under the same conditions.

On apparatus I and II the Philips tube 362619 produced hori-

zontality under these conditions. (Figure 32). The behaviour of this tube on apparatus III was next investigated. The third curve
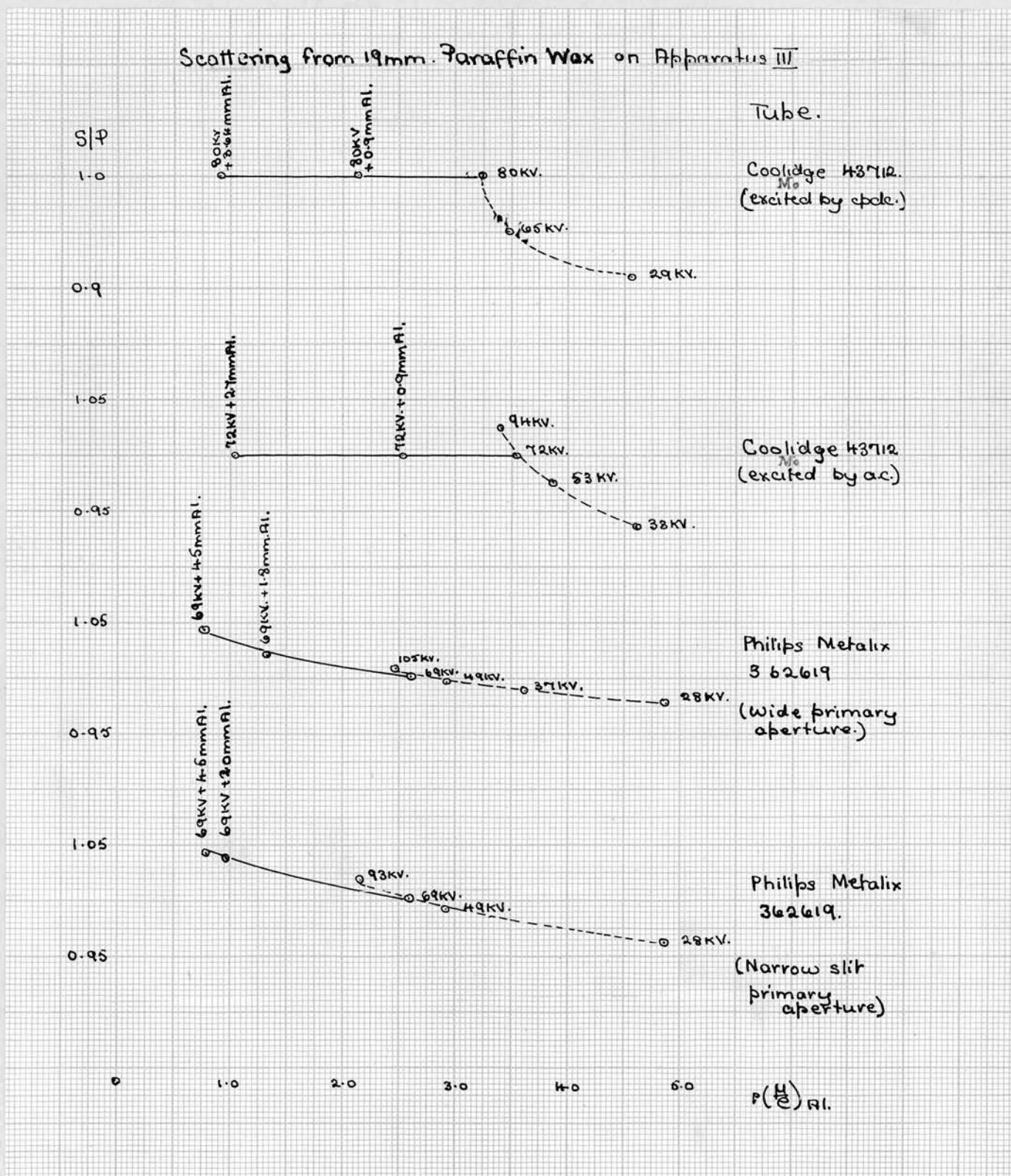

Figure 38

on Figure 38, shows the result obtained. The voltage-scattering curve is very much flatter than before and on inserting aluminium the value of S/P increases. In fact it is difficult to see where any break between the two parts of the experiment occurs. The mass absorption coefficient seems to be important, and the kilo-voltage immaterial. This type of result is quite different from any obtained on apparatus I or II, as S/P has never been found to increase on filtering out soft rays with these apparatus. (It should be noted here that this type of result has frequently been found on apparatus III by Mr. Stevens, when thick scatterers were used).

The lowest curve on Figure 38 shows that when the primary aperture was reduced to a slit (other details being unchanged) the form of the curve was unchanged. This conclusion was also valid for apparatus II as shown in Figure 34, (although individual tubes behave very differently on apparatus II and III). There is a systematic difference in this respect. It would seem that there is some factor which "pushes up" the values of S/P on filtering with apparatus III compared to apparatus I or II. When filtering causes horizontality on apparatus III (as top curve of Figure 38) the ratio drops on filtering on apparatus I (Figure 32). Tubes which show this horizontality on apparatus I and II, such as Philips 362619 and 382364, on apparatus III show an increase of S/P on filtering out the soft rays of the incident beam.

It is difficult to know what causes this difference between the results as obtained on different apparatus. In all cases the electrodes of the secondary and primary ionisation chambers are at the same distance from the mid-point of the scatterer, i.e. rays which reach the chambers in one case will reach them in all. Actually

there is a pronounced similarity between apparatus I and III, and
little between I and II in dimensions.   The ionisation chambers on
I and III are of the same size, and are usually filled with SO_2.
On II the chambers are much larger and are usually filled with air.
The primary and secondary apertures on II are very close to the
ionisation chambers, on I and III they are some cms. distant. But
in spite of these points of difference the results obtained on I and
II are similar and differ from those obtained on III.   The most
apparent respect in which III differs from I and II is in the cross-
section of the beam falling on the scatterer.   This is very small
in III.   But this cannot account for the discrepancy in experi-
mental results.   We have discussed results of experiments on
apparatus II which show that the cross-section of the beam does not
influence the shape of the curve.   In the course of these experi-
ments the cross-section of the beam on apparatus II was made equal
to that of III, but this did not appear to alter the results in any
way.

Another possible cause of the discrepancy was the scatter-
ers employed.   The same slab of 19 mm. paraffin wax was transferred
from apparatus I to II as needed.   That used on apparatus III
though similar was another specimen.   Figure 33 shows how the
occurrence of horizontality on filtering depends on the thickness of
the scatterer.   It might be that the scatterer used on apparatus III
was slightly thicker, or denser or of slightly different constitution
from that used on I and II.   An interchange of scatterers however
produced no effect on the results.

One interesting point which arises here is that lines of
positive and negative slopes are found among these results.   One

apparatus will show horizontality and either positive or negative slope, but not both.   The horizontal line would seem to be a limiting case and not a compensation effect, produced when the factors producing increase of S/P with filtering and those producing decrease of S/P with filtering are equal and opposite.   If it were a compensation effect when one set of factors was most in evidence lines of one sign of slope would be found, and when the other set was stronger the other sign would be shown.   But no apparatus has yet shown lines of both positive and negative slope.

To elucidate farther the difference between the sets of apparatus, experiments were conducted with thin scatterers.   A 3 mm. paraffin wax scatterer was inserted with a primary aperture of 1·5 mm. in diameter.
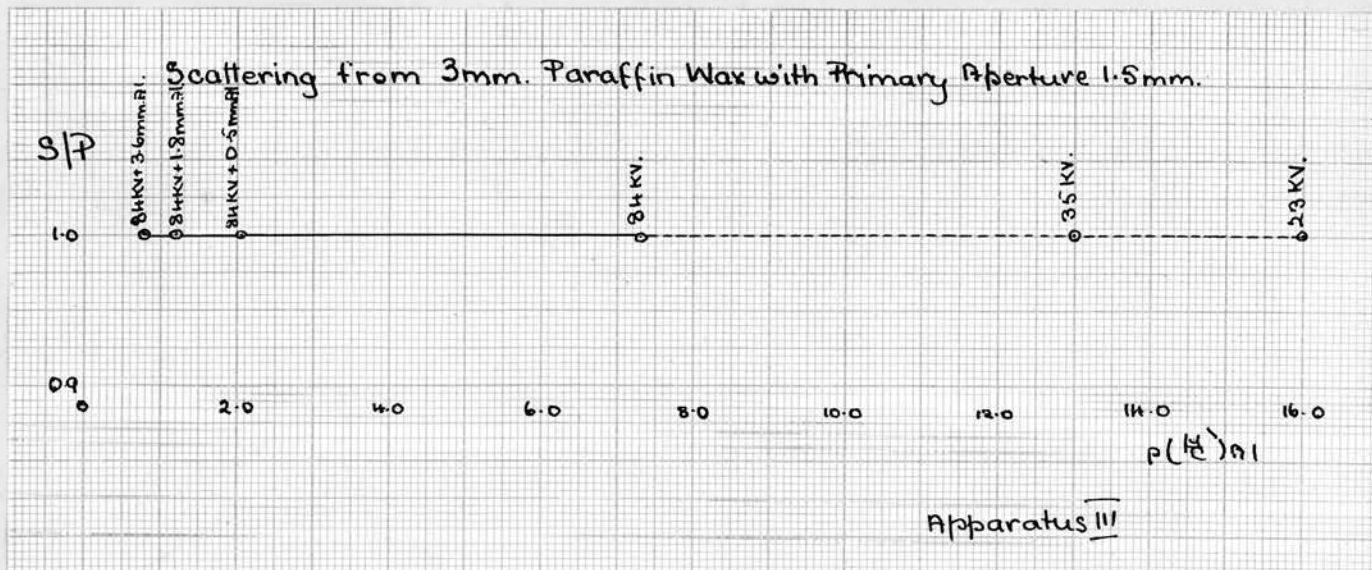

Figure 39

The tube was Philips 362619 excited by cpdc. high tension.   Although this was carried out on apparatus III the ionisation chambers were those of apparatus II.   The results shown in Figure 39 are markedly different from those shown in Figure 35 which was also obtained with

a 3 mm. scatterer.   On apparatus III there is complete horizontality;
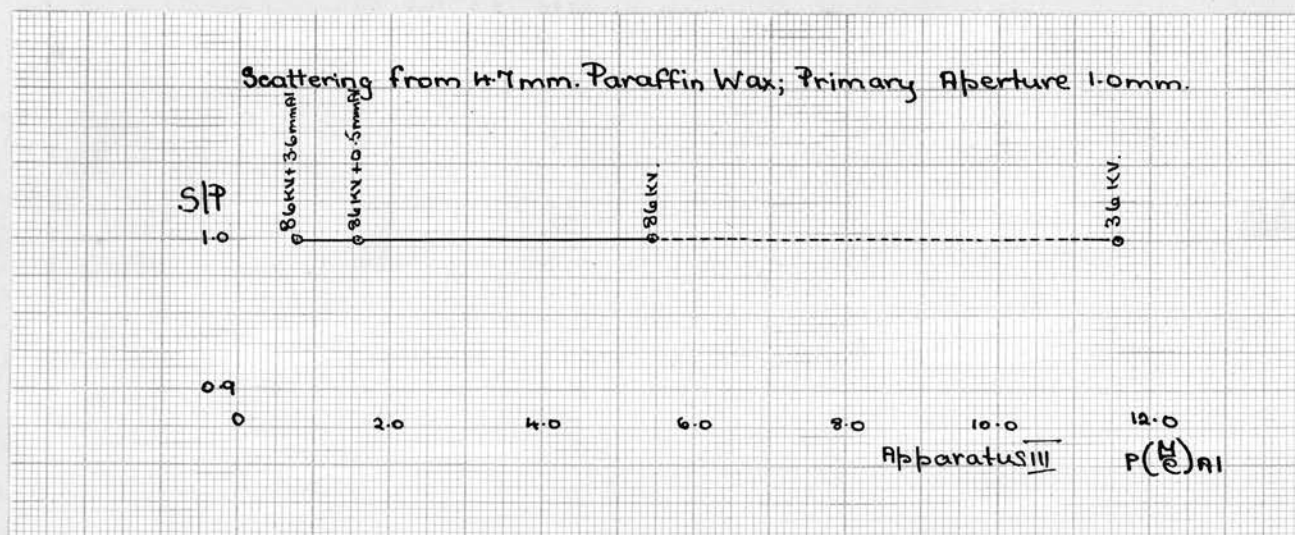on apparatus I the extent of the horizontal line is very short.

Figure 40

The result shown in Figure 40 is a very interesting one.
The scatterer, primary aperture and ionisation chambers were those
used for the experiment recorded in Figure 37.   In spite of these
identical conditions the results are very different.   The well-
marked horizontality on apparatus III is in sharp contrast to the
short extent of horizontality on apparatus II.

A further experiment was performed on apparatus III.
The scatterer was 8 mm. paraffin wax, and the primary aperture 1·5 mm.
in diameter.   The tube was Philips 362619.   The result of this
experiment is shown in Figure 41.   The horizontality in this case
is not so marked as in previous experiments, and disappears at both
the penetrating and the soft ends.   This must be due to the greater
thickness of the scatterer, as compared with the results given in
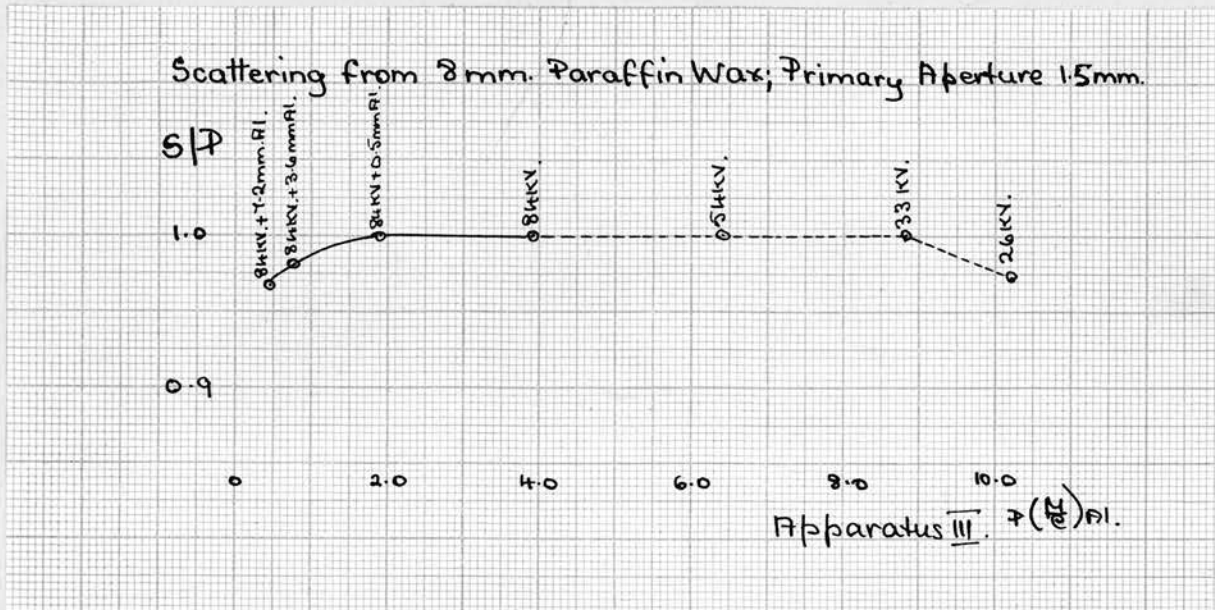Figure 40.   This precise experiment was not carried out on apparatus

Scattering from 8 mm. Paraffin Wax; Primary Aperture 1·5mm.

Figure 41

I or II, but from similar experiments it may be argued with con-
siderable certainty that were the voltage increased S/P would
increase indefinitely.   The insertion of aluminium would cause the
ratio to drop.

        It will be well to summarise briefly the chief differences
between the results as obtained on apparatus III and on apparatus
I or II.

(1) In the filtering experiment no horizontality is found on
apparatus III, whereas under certain well-known conditions a hori-
zontal region may be obtained on I or II.

(2) Where the scattering curve is obtained with voltage change only,
greater horizontality is found on apparatus III.

(3) When the scattering curve is horizontal with voltage, aluminium
inserted in the incident beam of III does not alter S/P in general.

On occasion a large amount of aluminium causes a small decrease of
S/P. When this experiment is done on apparatus I or II the value
of S/P decreases with the smallest amount of aluminium inserted.
(4) When a thick scatterer is used so that the voltage-scatterer
curve is not horizontal, and aluminium inserted at constant voltage,
horizontality may appear on all apparatus (but a tube which produces
it on apparatus III will not do so on I or II). If horizontality
does not appear on III, then S/P increases with increasing thickness
of aluminium while on apparatus I or II S/P decreases with increasing
thickness of aluminium.

Many experiments were carried out to determine what part,
or parts, of the apparatus were causing this systematic difference.
As has been mentioned above the ionisation chambers from apparatus
II were transferred to apparatus III, without in any way altering
the results as obtained from III. The scatterer and apertures on
apparatus II were also transferred to apparatus III, again with no
effect. These test experiments were carried out with many different
arrangements of thickness of scatterer and size of aperture but in
no case did the results show any resemblance to those obtained on
apparatus II, or any difference from those obtained on apparatus III.

As the layout of apparatus I and III was so similar and so
different from that of apparatus II, it was difficult to see how
this affected the results. However apertures and screens were added
to apparatus III to make the cross-section of the beams entering the
chambers the same as on apparatus II where the limiting apertures
were very near the chambers. This again produced no effect on the
shape of the curves.

The method of exciting the tubes cannot be held responsible

for this difference in scale, as the cpdc. apparatus on II had previously been used on III without causing any difference to the results. The ac. transformers were identical in type. It was however suggested that perhaps the actual lead screening as used on apparatus III might be in some way influencing the results. This was therefore replaced by an entirely new system of the same dimensions. The curves were not influenced at all, by this change.

It is unfortunate that this investigation, into the factors causing the difference in scale between the results as obtained from different apparatus, was initiated so near the end of the period of research. In the time available, only negative results have been obtained. This problem is one which demands further research, as its solution would shed much light on to the processes involved in these experiments.

THE CONNECTION BETWEEN SCATTERING AND FILTERING EXPERIMENTS.

In preceding pages it has been shown how horizontality may appear in the graphical results of both filtering and scattering experiments. In the former case the conditions favourable to its production are in general, high voltages, thin scatterers and small primary apertures. In the latter (i.e. scattering) case, thin scatterers and small apertures favour the appearance of horizontality, i.e. the conditions which favour the constancy of the S/P value in the one experiment, favour it in the other. Also conditions (such as the intensity and cross-section of the beam) which do not seem to have any effect on the ratio in the one experiment, are without effect in the other. It is thus natural to assume that there is some connection between these results. The following series of experiments was undertaken to determine the exact nature, (if any) of this connection.

A scattering curve was obtained using, as primary aperture, a clean drilled hole of 0·65 mm. in diameter, a 4·7 mm. thick slab of paraffin wax as scatterer, and Coolidge XP3 tube to supply radiation. The experiment was performed on apparatus I with the ac. transformer. It was found that the ratio S/P was constant from 90 kilo-volts to some point between 70 and 65 kilo-volts. The ratio dropped rapidly with lower voltages. Thereafter under identical conditions filtering experiments were performed at various voltages ranging from 59 to 86 kilo-volts. The results of these experiments are shown in Figure 42. In this figure the kilo-voltage scale belongs both to the filtering and the scattering experiment. The scattering curve has been plotted in the usual way, but the axes have been rotated through 90° in a counter-clockwise direction. Each filtering curve has the extreme left-hand point i.e. the unfiltered ratio plotted on the horizontal

line which represents the kilo-voltage exciting the tube when that
filtering curve was obtained.   (It should be noted that here, as
elsewhere, the ratios are expressed in terms of the greatest ratio of
any given curve as unity).   The vertical scale in all these filtering
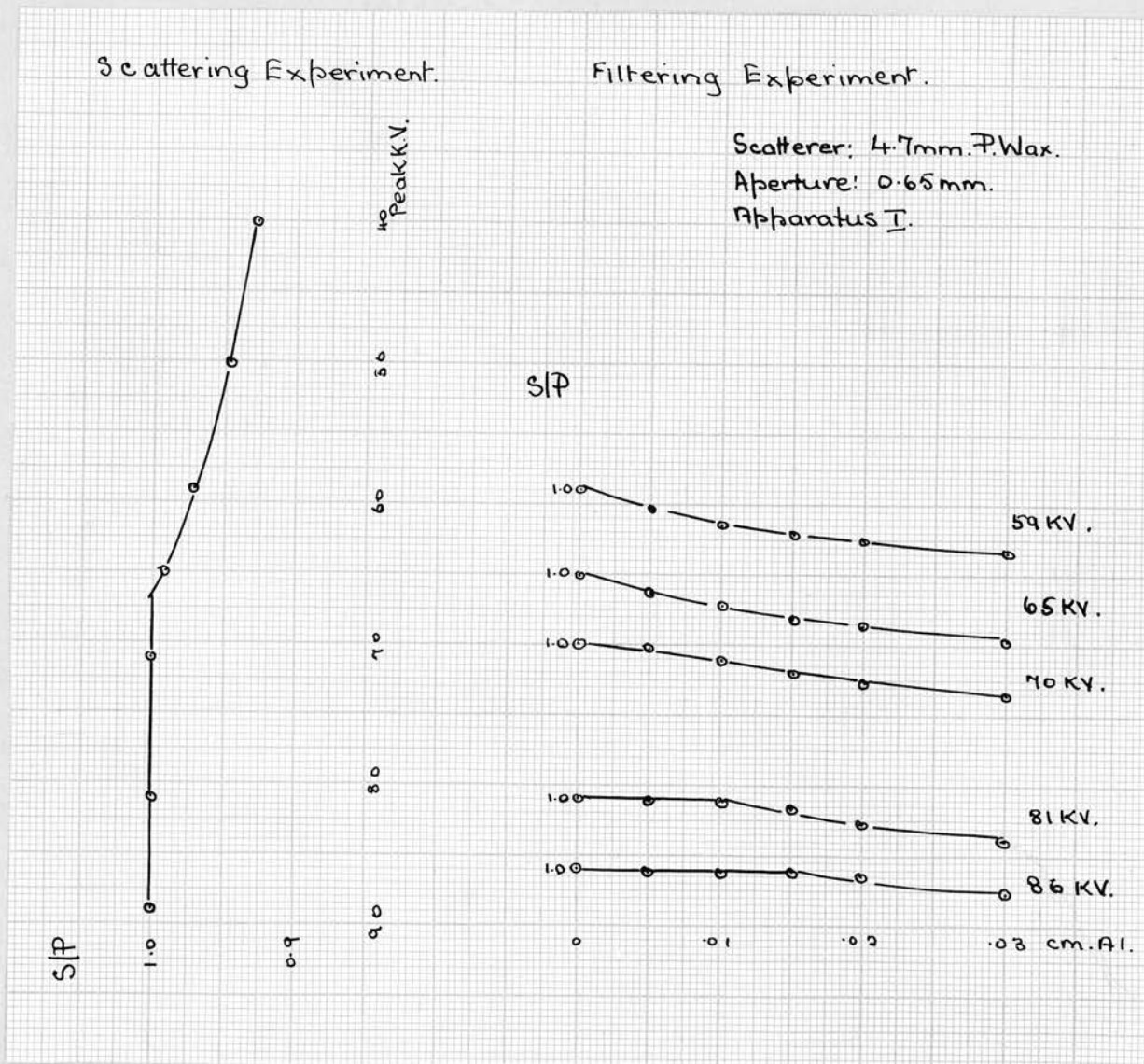curves is the same.   1 cm. represents a change of 5% in the initial
ratio.

Figure 42

The deductions to be drawn from this figure are clear.   At
low voltages when there is no horizontality in the scattering curve,
there is none in any filtering curve.   At high voltages horizontality

appears in scattering and filtering experiments alike.   In short to
produce a horizontal portion on the filtering curve we must choose
conditions which belong to a point on the horizontal portion of the
scattering curve.   This result is very simple but it must be verified
under all possible circumstances before it can be put forward as being
a general result.

On the following pages are discussed scattering and their
associated filtering curves, which were obtained at different times,
with different tubes excited in different ways, with all possible
arrangements of scatterer and apertures.   The scatterers varied in
thickness from 11 mm. to 3 mm., the apertures in size from a circular
hole of 1·2 mm. diameter to a fine slit of 0·2 x 7 mm.   In some cases
the scattering curve was first obtained and then the filtering curves;
sometimes the order was reversed.   Frequently one or two filtering
curves were obtained, then the scattering curve and finally more fil-
tering curves.   Occasionally a certain thickness of aluminium was
inserted in both beams and the voltage varied, thus obtaining points
on different filtering curves in turn.   But in no case did the order
of obtaining the points influence the result.

Firstly we shall consider the results of the combination of
a thick scatterer and wide aperture.   Figure 43 shows that when
x-rays are scattered at 45° from an 11 mm. paraffin wax slab, and
enter the primary electroscope through a hole 1·0 mm. in diameter
neither the scattering nor filtering curves show any horizontality.
These experiments were done on apparatus II with the Cuthbert Andrews
33983 tube excited by cpdc. high voltage.   The gas ionised was air.

The 11 mm. scatterer was replaced by one 8 mm. in thickness
and the series of experiments repeated.   No horizontality was found
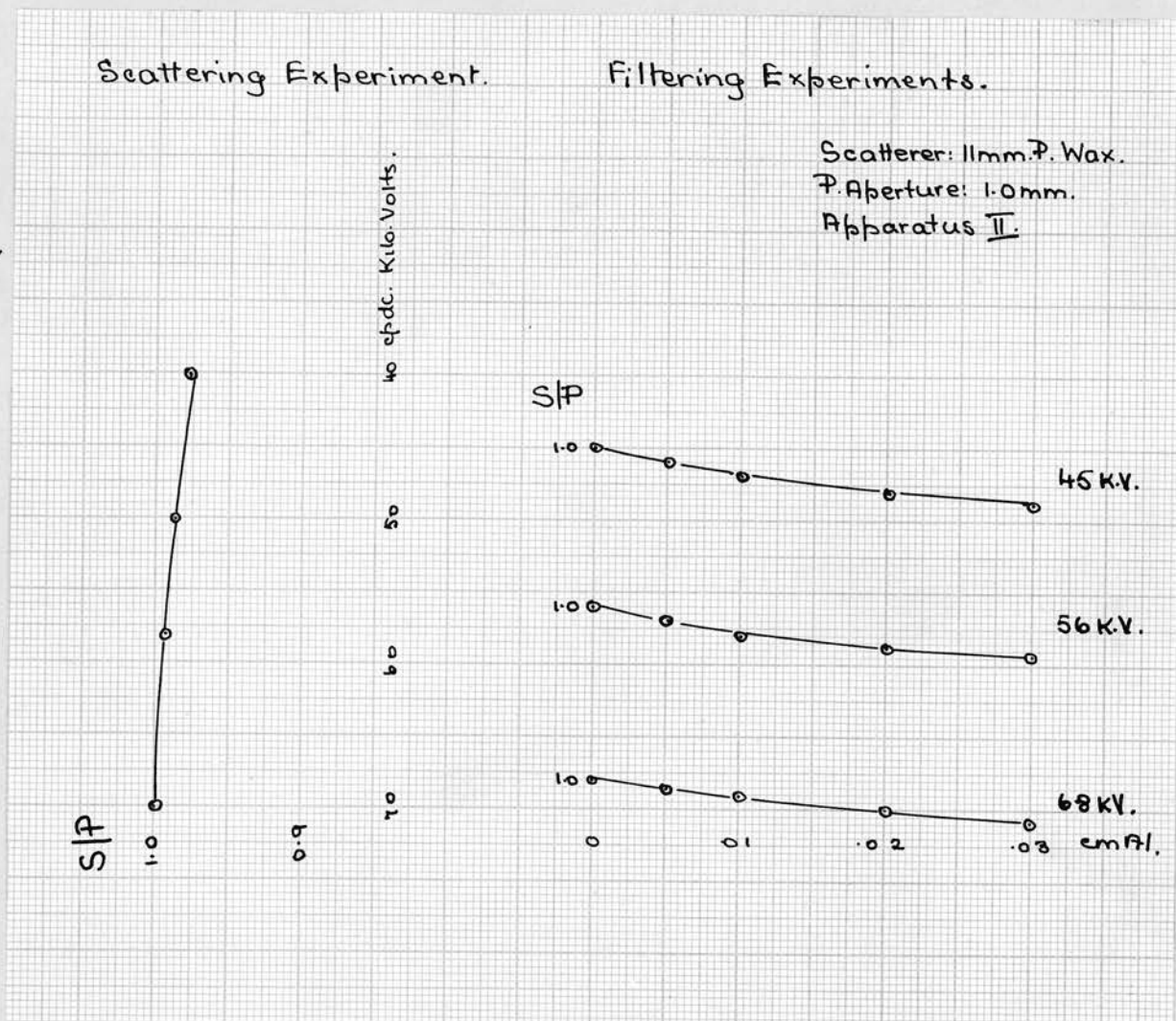
in any of the filtering or in the scattering curves.

Figure 43

If, however, the same scatterers, those of 11 and 8 mm.
thickness be used in conjunction with primary aperture of 0·6 mm. in
diameter, horizontality begins to appear as shown in the next figure.
The Coolidge XP3 tube excited on apparatus I by the ac. transformer,
was used with the 11 mm. scatterer and a single hole of 0·6 mm. in
diameter as primary aperture.   In the scattering curve S/P is seen to
be constant for values above 78 kilo-volts.   In the filtering curves
there is a short horizontal portion for those measured at 79 and 89
kilo-volts, while that at 69 kilo-volts has the greatest slope on the

91.

left-hand side.   Thus in this case filtering curves have slight

horizontal regions if they are obtained at voltages where the S/P

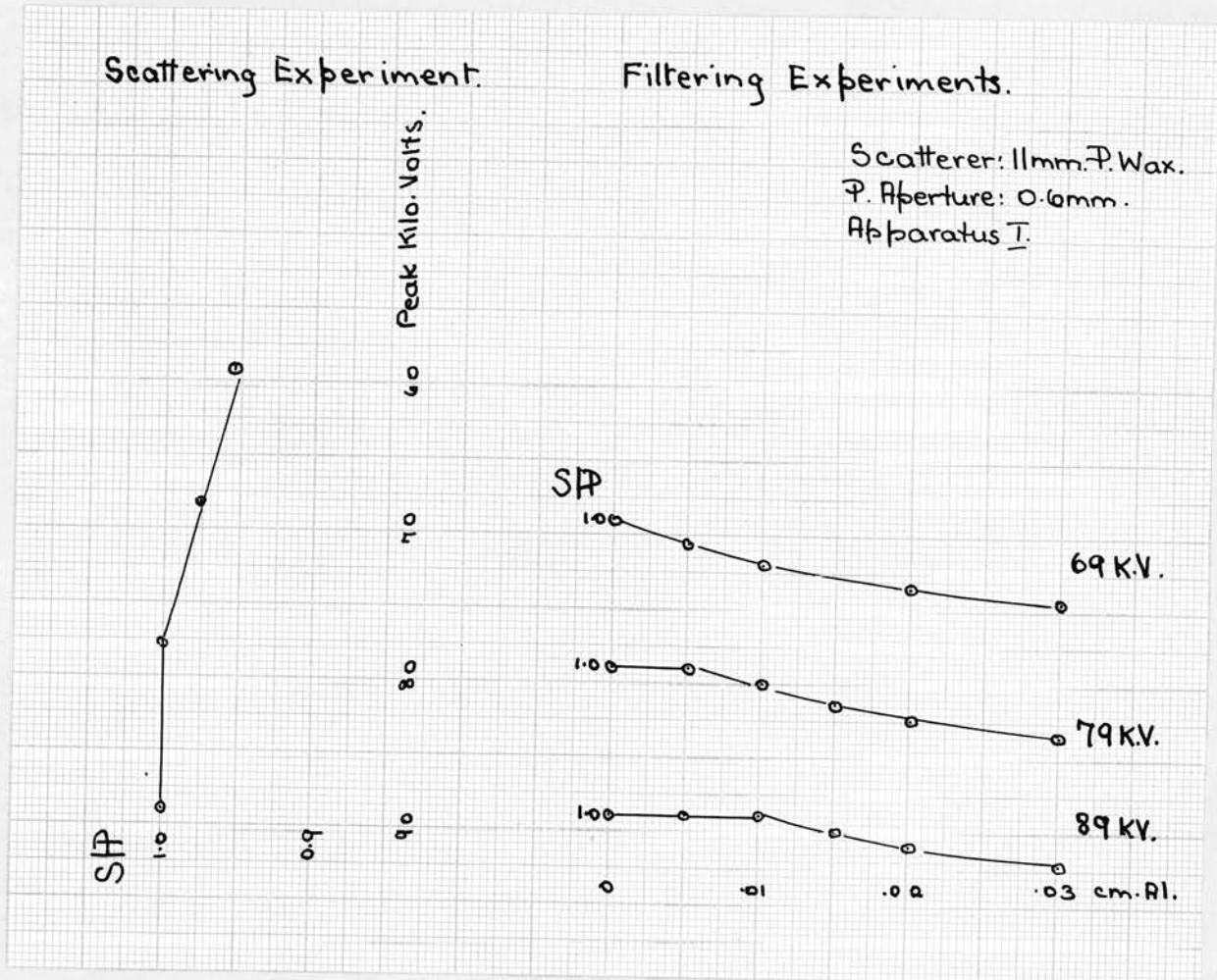value is unchanged by voltage change.

Figure 44

The rule given in the preceding sentence was found to be

verified also when the 11 mm. scatterer was replaced by one of 8 mm.

The tube used was in this case Siemens VS 1400 excited by ac. trans-

former.   Horizontality was found both in the filtering and scattering

curves above 70 K.V.   For lower voltages neither experiment showed

the least sign of horizontality.

The next series was performed on apparatus II with the cpdc.

source of high tension.   The tube was Cuthbert Andrews 33983, the

scatterer 8 mm. of paraffin wax.   An "edge effect" was introduced

into the experiment by leaving the holes of the primary aperture
uncleaned.   This consisted of four holes each of 0·6 mm. in diameter.
There were specks of dirt in the holes, and some of the edges were
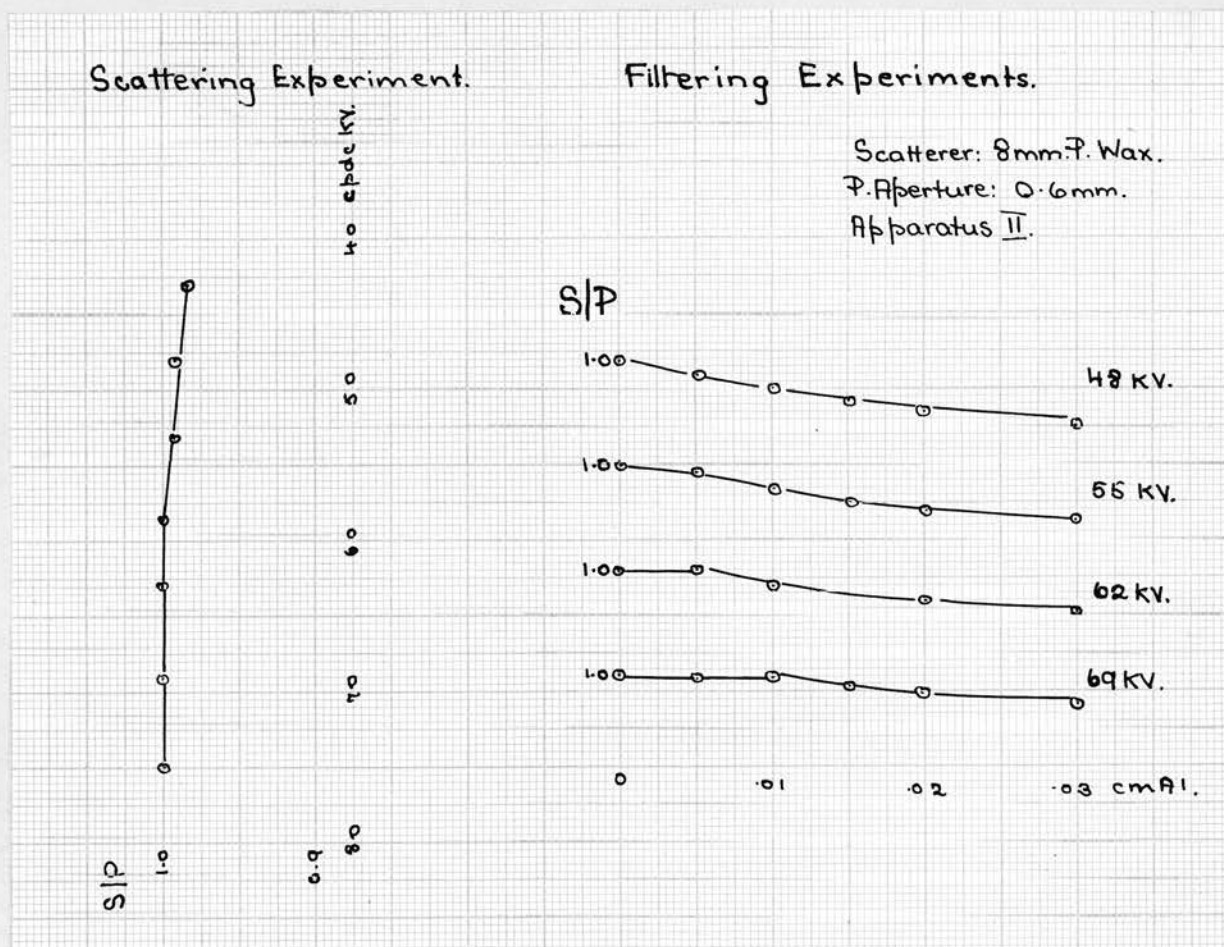imperfectly drilled.   Figure 45 shows that the scattering curve is

Figure 45

horizontal for voltages above 58 kilo-volts, and at 62 and 69 kilo-
volts the filtering curves show horizontality.   At 48 kilo-volts
neither curve shows horizontality.   Thus even with an edge-effect we
find no exception to the rule connecting the horizontality in these
experiments.

As has been shown above (pp. 36,57) narrow slit apertures
introduce exceptional results both in filtering and scattering experi-
ments.   These exceptions have been proved to be consistent in the
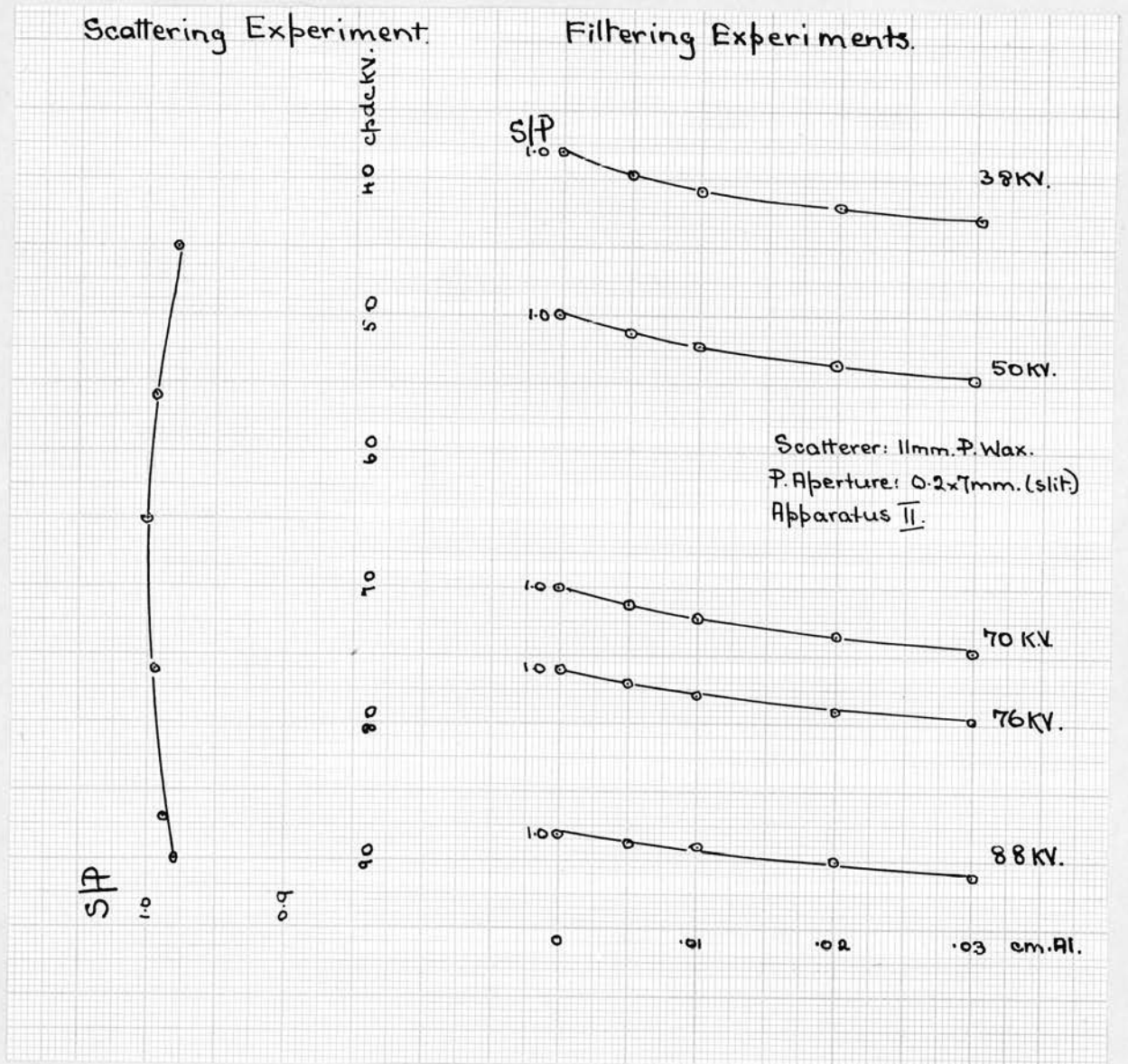light of the present work.

Figure 46

In Figure 46 are given results obtained by Siemens VS 1400 tube on apparatus II with a scatterer of 11 mm. paraffin wax and a primary aperture of 0·2 x 7 mm. Horizontality is nowhere to be seen, even though two of the conditions favourable to horizontality in the filtering experiment are present to a marked degree, high voltage and fine aperture. Indeed an 11 mm. scatterer used in conjunction with a 0·6 mm. primary aperture shows horizontality in either experiment. It is however clear that both filtering and scattering curves depart simultaneously from the expected behaviour. Thus in spite of the

unusual shape of the scattering curves in these experiments we find

no exception to the rule concerning horizontality.

Now we come to experiments carried out using thinner

scatterers.   A circular hole of diameter 1·2 mm. was used to limit

the primary beam, when radiation from Coolidge XP 3 tube was scattered

by a 4·7 mm. scatterer.   The experiments were done on apparatus I

using the ac. transformer. There was no horizontality in either
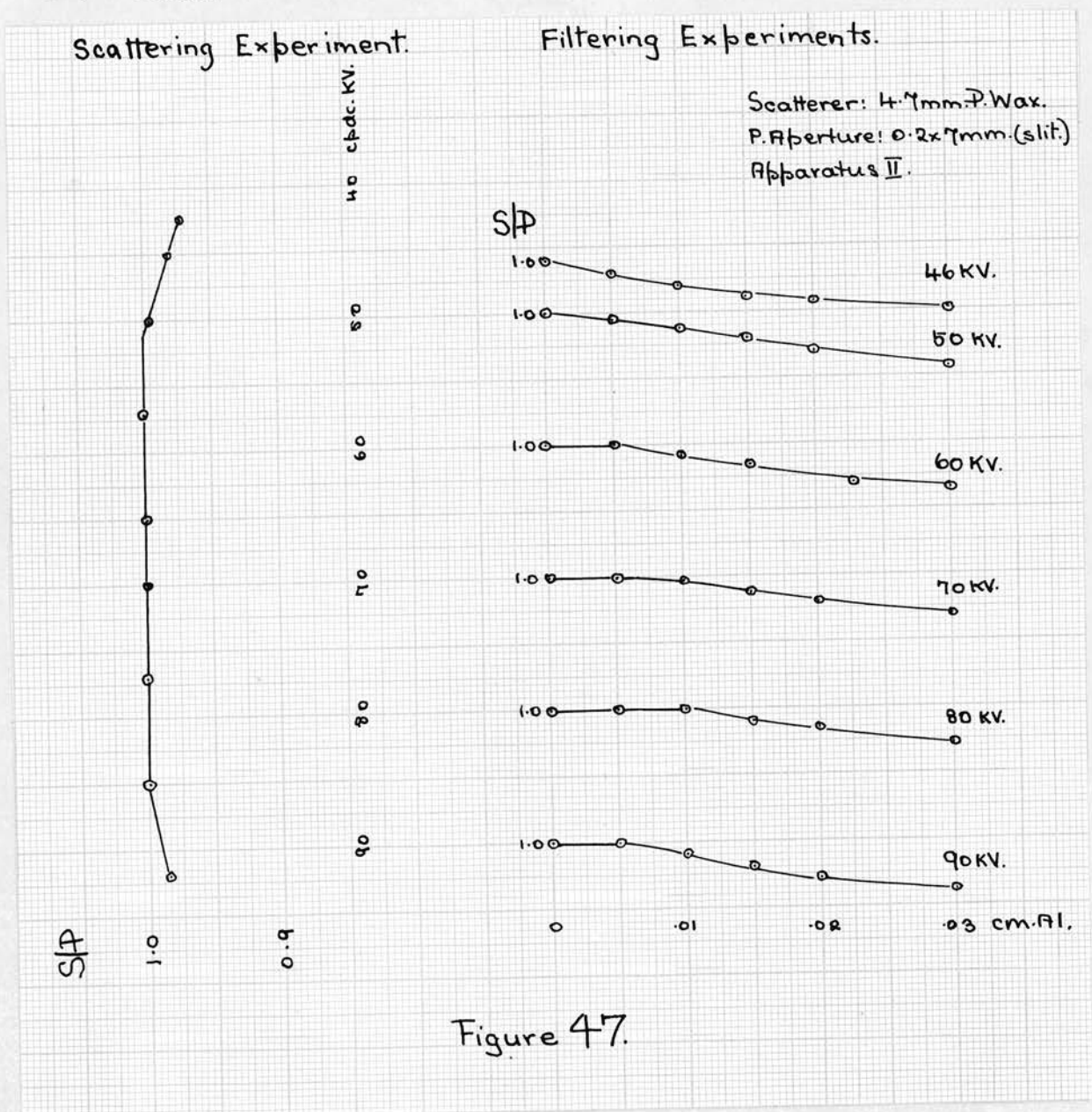
experiment.

Figure 47.

Figure 47 shows the results of filtering and scattering

curves performed on apparatus II with Siemens 234303 tube. The
scatterer was 4.7 mm. in thickness as before, but the primary aperture
was a horizontal slit 0.2 x 7 mm. At 90 K.V. the scattering curve
departs very slightly from the horizontal. (The departure though
slight, is larger than the observational error). At low voltages the
ratio S/P increases with voltage but is constant between 50 & 85 K.V.
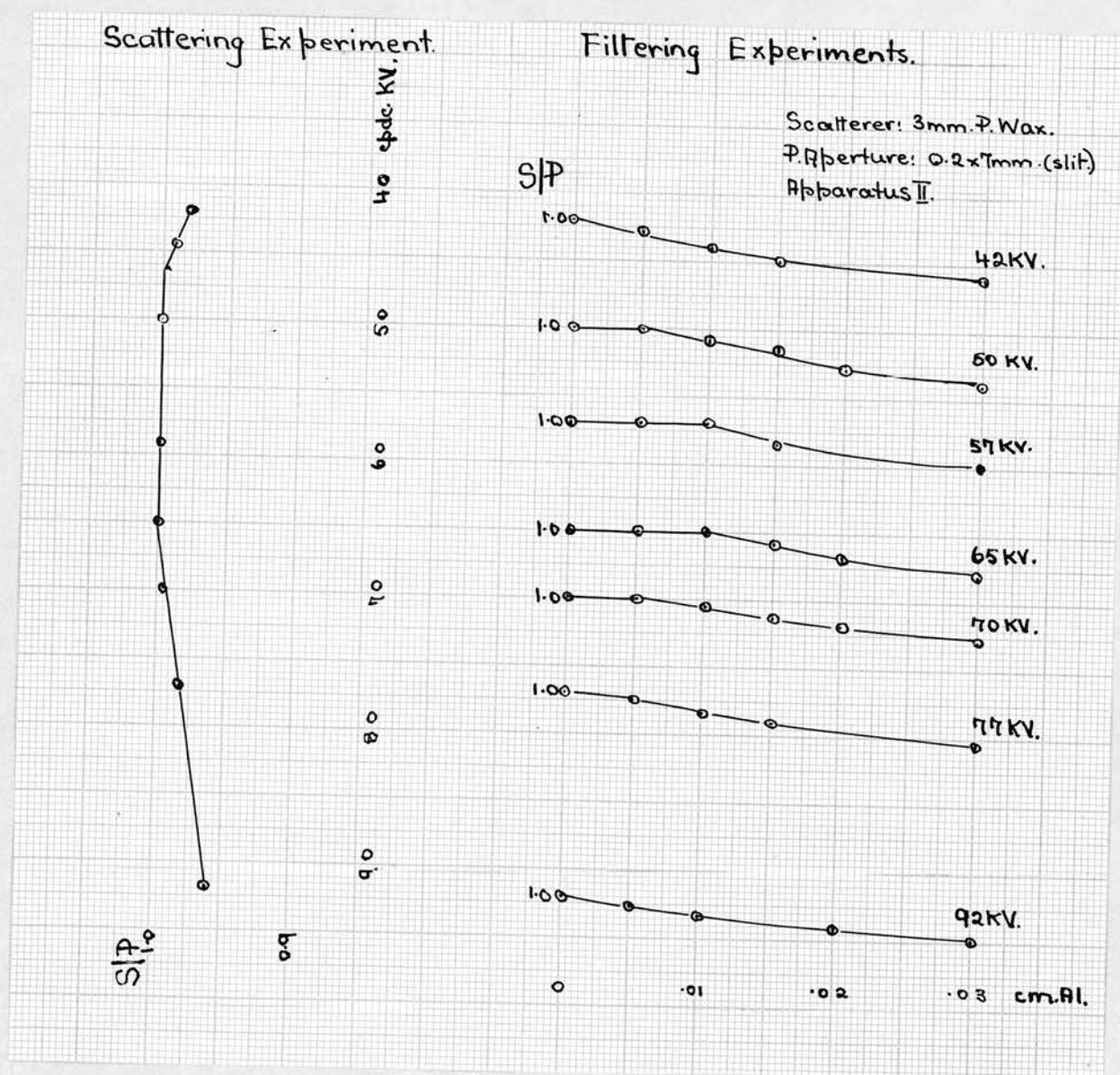

Figure 48

The horizontality in the filtering curve behaves in a similar way,
with well marked horizontality increasing with voltage in the usual
way. But at 90 K.V. the filtering curve is showing signs of decreas-

ing horizontality.   Thus this experiment also confirms the previous findings relating to horizontality in these experiments.

The decrease of S/P at high voltages is shown most clearly with thin scatterers, and the above series was repeated with a 3 mm. scatterer.   All other conditions were precisely the same. As can be seen in Figure 48, the horizontal portion of the scattering curve is much shorter, extending only from 47 - 68 kilo-volts.   The dip at the left-hand side is very marked.   The figure shows quite clearly that the region in which horizontality in the filtering experiment may be expected is over precisely the same range of voltage (46 - 68 kilo-volts).   This experiment confirms in a very marked way the relationship between the scattering and filtering experiments.

The 3 mm. scatterer was used on apparatus I in conjunction with a primary aperture of 0·6 mm. in diameter.   Siemens tube VS 1400, excited by the ac. transformer supplied the radiation.   Filtering curves obtained under these conditions are shown in Figure 18, owing to the great softness of the primary radiation the thinnest aluminium filter absorbed a large percentage of it.   Sheets of filter paper were therefore used instead.   At 75 and 83 kilo-volts a short initial horizontal portion was thus made visible in the filtering curve; at 53 kilo-volts no horizontality could be found.   The associated scattering curve was horizontal for all values of voltage above 55 kilo-volts.   Below this value S/P decreased with decreasing kilo-voltage. Thus even for very soft primary radiation the relationship under investigation holds.

Experiments were performed to see if a penetrating primary radiation would also show agreement with the above.   The Philips Metalix Tube 382364 operated on by cpdc. on apparatus II was used.

As this tube supplied a soft radiation 0·6 mm. of aluminium were inserted between the tube and the 11 mm. of paraffin wax which was the scatterer. The primary aperture consisted of 4 holes each 0·6 mm. in diameter. The scattering curve and two filtering curves were
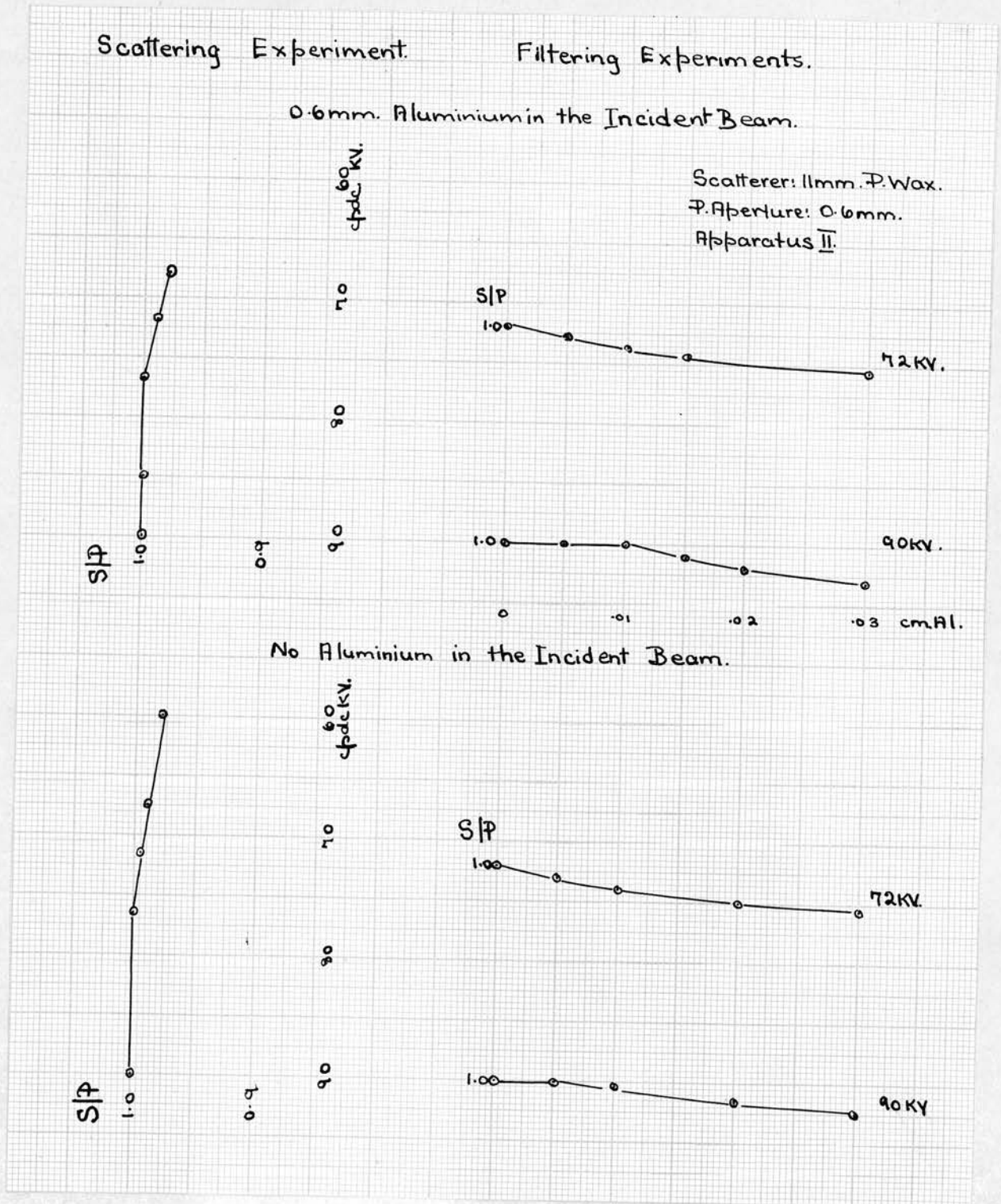

Figure 49

obtained.   At 90 kilo-volts $\frac{1}{p}\left(\frac{\mu}{e}\right)_{Al}$ = 2·0.   The upper part of Figure 49 gives these results.   Above 77 kilo-volts the scattering curve is horizontal.   The filtering curve at 72 kilo-volts shows no sign of horizontality while that at 90 kilo-volts has a well marked horizontal portion.

The lower part of this figure shows the results of the same experiment performed without any aluminium in the incident beam, all other experimental details being unchanged.   At 90 kilo-volts $\frac{1}{p}\left(\frac{\mu}{e}\right)_{Al}$ = 3·3.   In spite of this marked difference in the quality of the incident radiation in the two experiments no marked difference can be seen in the results.   From this we deduce that the quality of the incident radiation does not affect the relationship between the filtering and scattering experiments.

In the above comparison between scattering experiments and horizontal regions in filtering curves, we have only considered cases of the scattering curve where S/P is constant with varying voltage. There is however the other, and rarer, type of horizontality in which S/P is constant for a given voltage on the tube and varying mass-absorption coefficient of the primary radiation.   This is obtained by inserting various thicknesses of aluminium between the tube and the scatterer.   This type of horizontality is discussed above (pp.70-86) The behaviour of the filtering curves over the region of voltage and mass-absorption coefficient which gives a horizontal scattering curve was investigated.   Philips tube 382364 was operated on by cpdc. on apparatus II.   The primary aperture was 1·5 mm. in diameter and the scatterer was paraffin wax, 19 mm. in thickness.   The gas ionised was air.   On the left of Figure 50 the scattering curve is shown. At 70 kilo-volts S/P is constant for all values of mass-absorption

coefficient.   Filtering curves at 70 kilo-volts are shown for four

values of mass-absorption coefficient.   In every case a smooth slope

was obtained.   This result would appear to be at variance with those

given above since horizontality in the scattering experiment is not

associated here with horizontality in the filtering experiment.   This
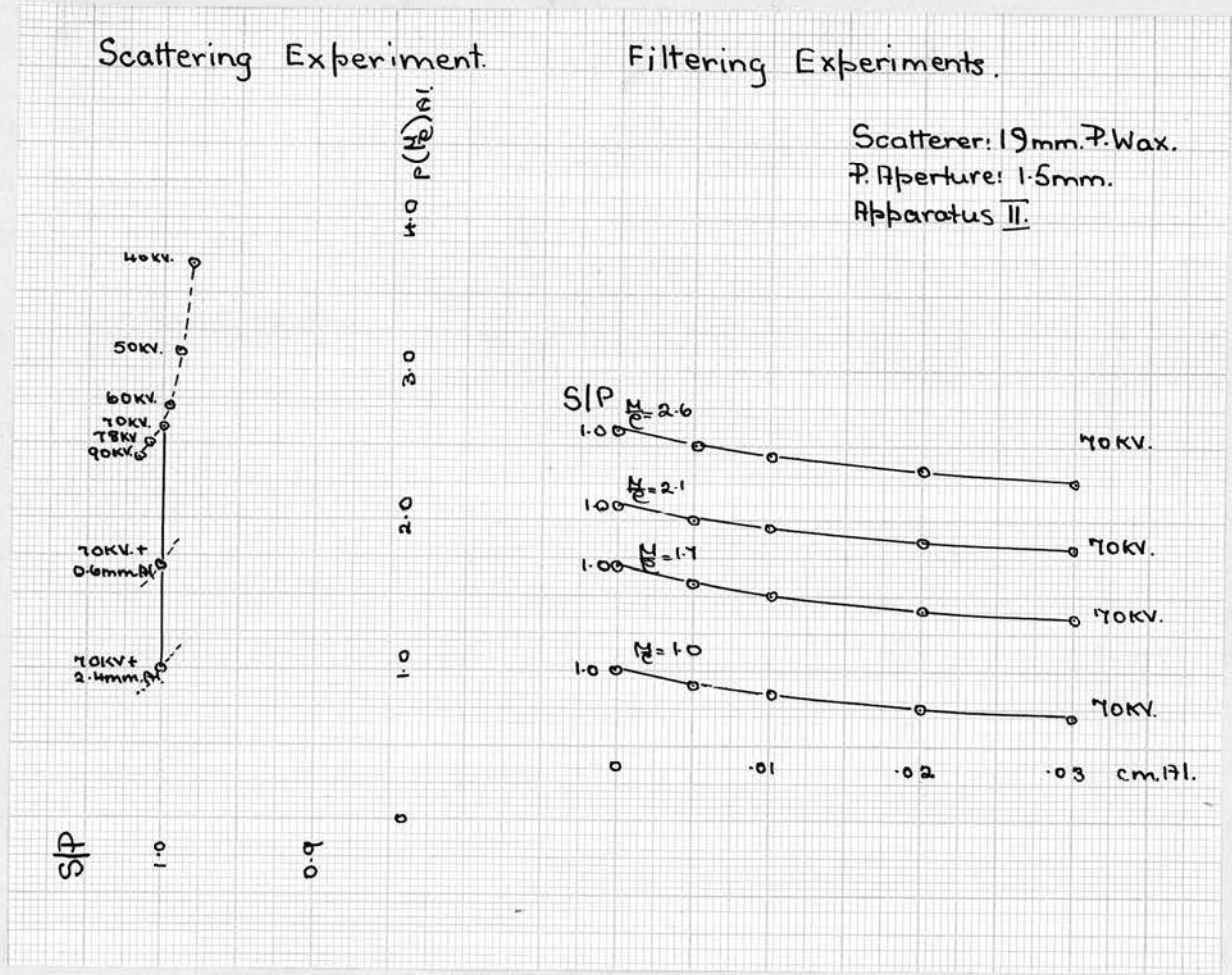

Figure 50

discrepancy disappears however if it is realised that a variation in

the voltage at each point at which filtering curves are obtained,

results in a variation in S/P, i.e. with respect to voltage the scat-

tering curve is not horizontal at any point.   (This is indicated by

short broken lines through the points on the horizontal line).   From

this point of view the conclusion is that neither scattering nor

filtering experiment shows horizontality.

Another apparent exception to the rule connecting the horizontalities is shown in Figure 51. These results were obtained with Coolidge XP3 tube excited by cpdc. on apparatus II. The scatterer was 4·7 mm. Paraffin Wax and the primary aperture 1·0 mm. in diameter. Above 75 kilo-volts S/P is constant with increasing voltage to 90 kilovolts. When the softer rays are filtered out with aluminium the ratio drops. In spite of this non-horizontality of the scattering curve when $\frac{1}{P}\left(\frac{\mu}{e}\right)_{Al} = 1\cdot55$, the filtering curve at this point shows an initial horizontal portion. The discrepancy disappears however when the scatterering curve is considered with respect to voltage. The short broken line on the figure indicates that if the voltage at this point is varied, keeping the thickness of absorbing aluminium constant the ratio S/P remains constant. Thus from the point of view of voltage change we have horizontality in the filtering curve associated with horizontality in the scattering curve. This result is not an isolated one. In every case where a decrease of S/P is produced by hardening the incident radiation with aluminium at constant voltage, the filtering curve shows horizontality if the scattering curve is horizontal with voltage. It would seem as if the voltage-produced-horizontality is of greater fundamental importance than the horizontality produced by filtering out soft rays. The latter shows no influence on the results of the filtering experiment, while the former is, as we have seen, very closely connected with it.

EXPERIMENTS PERFORMED ON APPARATUS III.

The experiments described above have been performed on apparatus I or II. The conclusions to be drawn are, it appears,
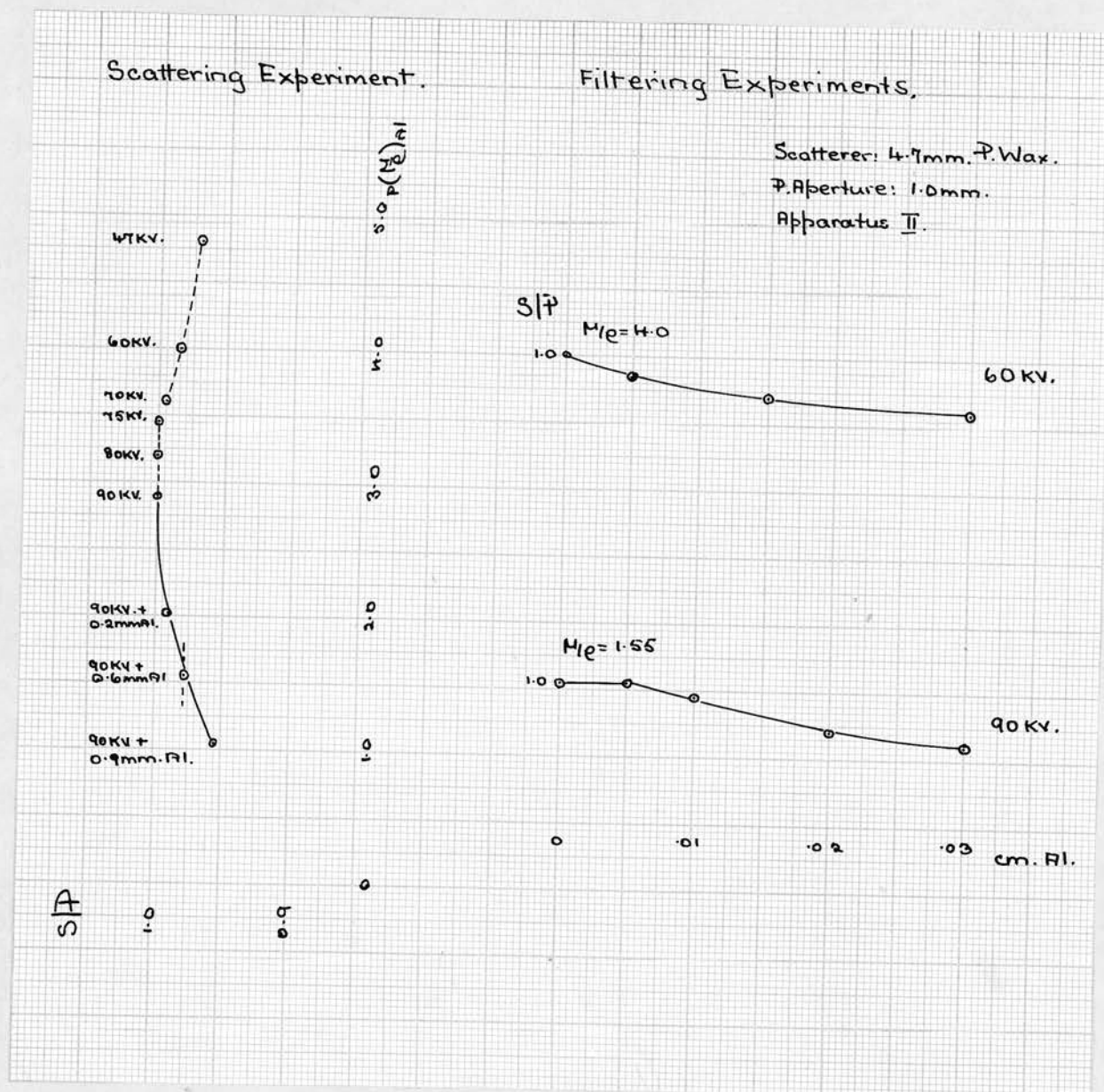
Figure 51

valid for both.   This investigation into the relationship between
scattering and filtering experiments was next extended to apparatus
III.   As has been noted above (p. 66) results obtained on this
apparatus do not agree entirely with those obtained on the other two.
In the course of many filtering experiments performed on apparatus III
Mr.Stevens has never found any initial horizontal portion.   Marked
horizontality in the scattering experiment has been obtained.   The
following experiments were therefore carried out in collaboration

with Mr.Stevens.

A paraffin wax scatterer 8 mm. thick was used with a primary
aperture of 1·5 mm. diameter.   The tube was Philips 362619 excited
by the cpdc. apparatus.   This combination of scatterer thickness and
of aperture width would not give any horizontality in the scattering
or filtering experiments if performed on apparatus I or II.   Figure
52 shows the marked horizontality in the scattering experiment. Three
filtering curves were obtained.   No sign of horizontality could be
found.   A very large number of estimations of S/P were made for the
unfiltered beam, and for the beams passing thro' the thinnest filters.
At 80 kilo-volts the thinnest filter absorbs less than 12% of the
primary radiation.   It is quite definite that there is no horizontal-
ity in the filtering experiment on apparatus III.

The most obvious difference between the sets of apparatus II
and III lay in the size of the ionisation chambers (see p. 14). Those
of apparatus II were therefore transferred to apparatus III and another
series of experiments was performed.   The same tube Philips 362619 was
used, and the same primary aperture 1·5 mm. in diameter.   The scatter-
er was changed to one 3 mm. thick.   Extreme horizontality on scatter-
ing is seen in Figure 53 but none at all in filtering.   From the very
rapid drop in S/P in the filtering curve at 53 kilo-volts it is clear
that no horizontality can be expected there.   At 84 kilo-volts the
initial slope though small is undoubtedly real.

Thus on apparatus I and II we see that there is a definite
relationship between horizontality in the filtering and scattering
experiments, i.e. conditions which give horizontality in the scatter-
ing experiment give initial horizontality in the filtering experiment.
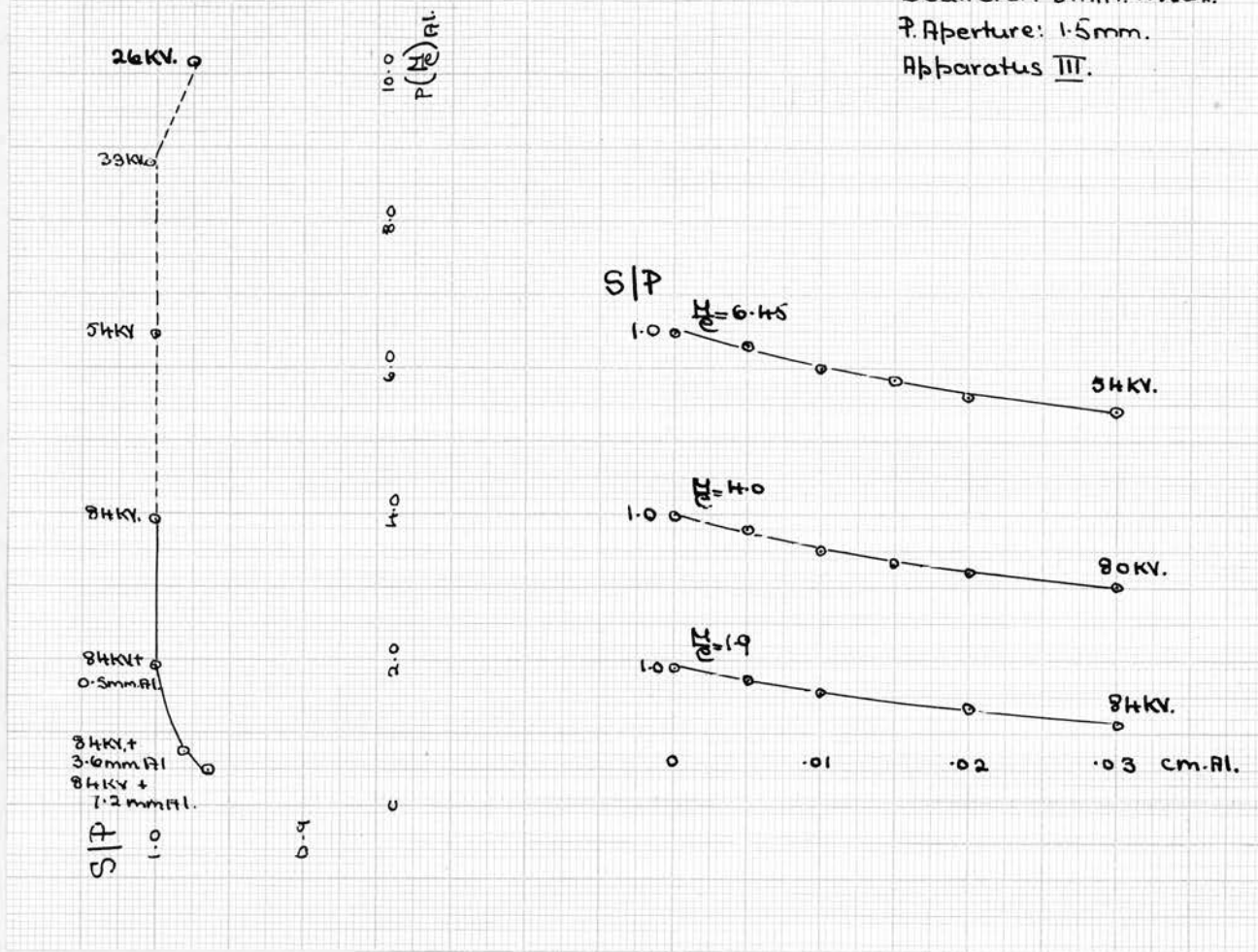On apparatus III no relationship of this kind holds.
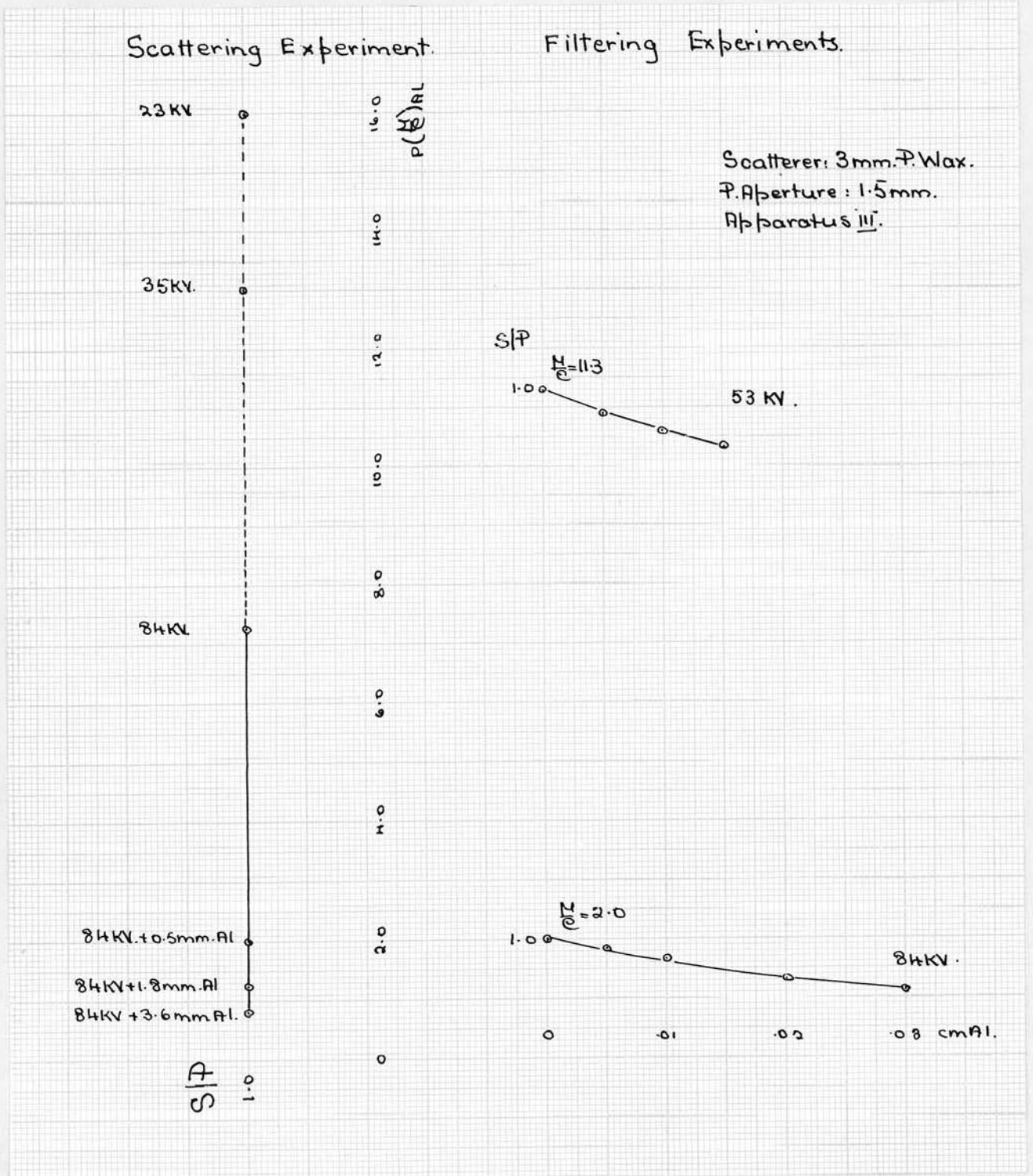
Figure 52

Figure 53

DISCUSSION.

(a) Filtering Experiment.

In the Introduction, deductions were made both from classical and quantum theories as to the form of the graphical result of the Filtering Experiment. The results obtained agree with neither theory in every respect. The horizontality, indicating equality of absorption, as predicted by the classical theory appears only under certain conditions and then only when thin layers of matter have been traversed. The approximately exponential curve predicted by the quantum theory appears under other conditions, and is indeed that most frequently obtained. But a result which shows initial horizontality can be turned into one whose steepest slope is at the beginning by slight alterations of certain conditions (e.g. size of primary aperture) which according to no accepted theory, have any influence on the result.

To explain this initial horizontality on the classical theory we must assume that subsequent transmission through matter is necessary for the evidence of quantum scattering. According to the simplest form of the classical theory the rays leaving the scatterer are identical with the primary rays, and therefore no amount of aluminium in the beams would alter the ratio. Thus the secondary rays as they leave the scatterer must be modified in some way since every graph sooner or later shows change of S/P with x, Some other explanation of the horizontality must be sought. If wave-length be changed, yet no change appears in the absorbability, (excluding the possibility of any chance compensation against which there is very strong evidence) it suggests that absorbability is a measure of something more fundamental even than wave-length.

It has been suggested that there is some compensation effect between factors tending to reduce the value of S/P on filtering and those tending to increase it. This compensation would therefore produce horizontality when conditions were such that these factors balance. Were this so, initial positive and negative slopes might be expected among the results of filtering experiments according to which set of factors was the dominant one in that particular experiment. An examination of very many results does not show even one in which S/P increased on filtering, nor does it show any evidence of a small decrease of S/P initially i.e. a small negative slope (except under transition conditions). For small thicknesses of matter traversed the ratio of the secondary and primary ionisations is either constant (within narrow limits of accuracy) or else it decreases rapidly with increasing thickness of matter traversed. Careful experiments have been conducted with the express purpose of detecting slight deviations from the horizontality (if they exist). The greater care and accuracy attained only serve to confirm the horizontality.

It is known that the smaller the primary aperture the greater the chance of horizontality. The most likely way in which the aperture could affect the results would be by altering the mass-absorption co-efficient of the primary beam. Direct experiment (by measuring the thickness of aluminium required to reduce the ionisation of the beam by 50%) does not show any influence of the size of the aperture. It is, however noteworthy that this horizontality only extends over at most, 20% diminution of the ionisation of the primary beam. Two graphs, recording results of experiments in which the only differing factor was the aperture, have very different

values of S/P for small thickness of filter, but when 50% of the
primary beam has been absorbed, little difference can be detected.
Thus it is, that this method of measuring mass-absorption coefficient
shows no difference between these cases.   Therefore a very thin
sheet of aluminium was inserted in the primary beam in the two cases,
of wide and narrow apertures, and the percentage absorbed was
measured.   The accuracy of experiment was unfortunately not
sufficiently high to state definitely the difference.   It is very
small, but must be present to account for the difference in graphical
result.   The physical difference between wide and narrow apertures
is chiefly in the ionisation processes.   When the beam passes through
a very narrow aperture the ions in the chamber are formed outside
the beam.   But when a wide beam enters the chamber the ions are not
entirely outside the beam.   Radiation therefore falls on the ions
themselves.   The consequences of this important difference in the
ionisation processes are not yet known.

The scatterer plays the part of a filter as well as a
scatterer.   But the influence of the thickness of the scatterer on
the results cannot be due entirely to its filtering power.   If 3 mm.
of paraffin wax are inserted between the tube and an 8 mm. paraffin
wax scatterer, the rays pass through 11 mm. of wax, and yet the
results obtained agree entirely with those for an 8 mm. scatterer
and are unaffected by the extra filter inserted between the tube and
scatterer.   (Figure 49 gives the results of experiments in which the
effect of aluminium between the tube and scatterer is investigated.
It also shows that it is the thickness of scatterer which actually
sends rays into the secondary chambers that is effective)

When we are considering the effect of the thickness of the

scatterer, the influence of multiple-scattered radiation and oblique rays from the scatterer must be reviewed.   But these rays are softer than the ray scattered once at an angle of 90° to the primary. Therefore instead of these factors tending to keep S/P constant, they produce an effect which must tend to make S/P decrease more rapidly than anticipated for small thickness of aluminium.

It seems therefore unsatisfactory to attempt to explain the results of these experiments by the processes postulated by the classical and quantum theories.   Even a qualitative explanation is almost impossible while a quantitative discussion is out of the question.   We can only conclude that ionisation and absorption processes for heterogeneous beams are not the simple phenomena postulated by either the classical or the quantum theory.

That this equality of absorption of secondary and primary beam is a reality is shown by the following considerations.

(1) Over this initial region either the rate of decrease of S/P is greatest or it is non-existent (except under transition conditions in which the apparent "shoulder" effect is most probably due to a very short initial horizontality, less than one filter thick, and then the usual decrease occurs).   Lines of small positive or negative slope do not occur.

(2) The most careful measurements of S/P only confirm the equality of ratio.   No systematic variation has been found.

(3) The conditions controlling this equality of absorption are definite and simple - thin scatterer, thin absorbers, small apertures, and penetrating rays.

(4) Slight variations in the energy-wavelength distribution of the beam e.g. by use of another tube, do not affect the phenomena.

(5) It is definitely connected with the phenomena of the scattering experiment.

The J. Discontinuities.

Many of the workers[1] in this laboratory have recorded the appearance of the J. Discontinuities.   These occur at certain definite thicknesses of aluminium in the filtering experiment.   These are shown in abrupt changes of S/P of the order of 7%.   Between these discontinuities the value of S/P may remain constant, or may decrease in an approximately exponential manner.

One of the most important features of this phenomenon is that it is reproducible over short periods only.   Identical experimental arrangements produce identical results for a short period and then the type of result obtained changes.   Although several factors have been found to influence the result no single condition has been found to control the appearance of this phenomenon.

These discontinuities however, when they appear tend to do so at certain definite values of the mass-absorption coefficient of the primary beam.   Thus they would seem to depend on some statistical property of the beam, which is most probably not yet recognised.

It is clear that no experiment described in the preceding pages shows an example of this phenomenon.   There are discontinuities of gradient in the filtering graphs, but none of absolute value. This is also true for the many filtering experiments which have not been included in this work.   As far as possible conditions were made identical with those in which discontinuities had been recorded by Miss Mackenzie and Dr. Kay.   But no discontinuity in the ratio of the intensities of ionisations has been found.

[1] see pg 115.

(b) <u>Scattering Experiment</u>.

It might be suggested that the constancy of the value
of S/P in the scattering experiments, when the only variable is
the voltage is due to a compensation between various factors each
of which tends to alter this value.   Chief among these factors
are, the scattering coefficient of the modified beam, and also of
the unmodified, the ratio of modified to unmodified secondary rays,
the ionising power of the various wave-lengths, the polarisation of
the primary beam, the percentage of re-scattered radiation, and the
fraction of radiation absorbed in the scatterer.   Over the range
of voltage used, (normally 30 KV to 90 KV, which can be extended to
20 to 100 KV) some of these factors vary by a considerable fraction.
Yet we know S/P does not vary by 1% over a range of voltage where
there is horizontality.   This range varies according to the condi-
tions but is frequently very extensive.   The approximate magnitude
in the variation of these effects is, scattering coefficient 30   %,
ionising power 30%, polarisation of the primary beam 8%.   This last
magnitude has been obtained by Khubchandani [2] and Pal [3] in this labora-
tory.   The ratio of modified to unmodified scatterer may vary by
fully 5% [4] under the conditions of the present work.   Also with a
scatterer of some 5 mm. in thickness when a beam of medium hardness
is used there may be as much as 8% [4] of the total scattered radiation
in the form of twice scattered radiation.   This effect of polarisa-
tion must be considered more deeply.

It is well known [5] that the primary beam of radiation from
an x-ray tube is partially polarised.   It may be considered to
consist of two parts, one unpolarised, the other plane polarised,
with the electric vector parallel to the cathode stream.   When the

latter is scattered no rays from it enter the secondary chamber,
(placed as in these experiments) which therefore registers only the
rays scattered by the unpolarised component.   The percentage of
polarisation of the primary beam is greatest for low voltages and
least for high.   Thus the fraction of the beam which is effective
in the secondary chamber increases as the voltage increases.   The
experimental results must be corrected for this effect before they
can be compared with the theoretical predictions.   Only a roughly
quantitative comparison is attempted here as high accuracy is
impossible owing to the heterogeneous nature of the beams.

Let Su denote the ionisation produced by the secondary
beam from the unpolarised portion.

Let So denote the ionisation which would be produced were
the polarised component replaced by one of equal intensity but
unpolarised.

Then $Sc = Su + So$,
where Sc denotes the entire secondary beam, assuming the primary,
unpolarised but unchanged in intensity.

Now the deduction from the simple classical theory to the
effect that

$$S/P = constant$$

for all wavelengths, assumes that there is no change of polarisation
of the primary beam with wavelength, i.e. Sc is considered.   But
the experimental results give the ratio Su/P.   Rewriting the above
equation we obtain

$$\frac{Su}{P} = constant - \frac{So}{P}$$

The term So/P decreases with decreasing voltage.   If Figures 24-26

are considered it is seen that this shape of curve is obtained when wide apertures and thick scatterers are used. Thus to a first approximation the classical theory is found to account for the experimental results under these conditions, but it is under these conditions i.e. wide apertures and thick scatterers that the results of the progressive absorption experiments showed the difference of absorbability to be expected on the quantum theory.

It also follows that the extensive horizontality obtained with apparatus III (Figures 39,40) which at first sight appeared to agree with the classical theory is modified when the polarised portion is considered. These experiments show that

$$\frac{Su}{P} = \text{constant.}$$

i.e. $\frac{Sc}{P} = \frac{Su + So}{P} = \text{constant} + \frac{So}{P}$

i.e. the result corrected for polarisation is a curve concave upwards with the greatest ordinate for the lowest voltage. This does not agree with either the classical or quantum predictions.

Certain well-marked features of the experimental results remain unexplained by either theory. The sudden relative decrease in the ionisation produced by the secondary beam at low voltages (e.g. Figure 29) cannot be attributed to polarisation since the latter has no abrupt change at any point. Also the voltage below which this sudden decrease takes place is not fixed but depends on other factors.

It is obvious from the above considerations that a compensation of the nature described on page 110 does not take place. Also were a horizontal line due to a perfect compensation, we should expect slight alterations in the conditions e.g. a different energy-

wavelength distribution due to the use of a different tube, to cause slight deviations from horizontality.   This is never observed. Either the graph of S/P shows horizontality, with perhaps a sharp decrease at low voltages, or it is curved concave downwards.   Even the low voltage end of such a non-horizontal result differs from the low voltage end of a graph with horizontality at higher voltages.

The results of the scattering experiment are remarkably simple.   Over a definite range of voltage the ratio of the ionisations produced by the secondary and primary beams is unchanged.   The conditions of size of aperture, thickness of scatterer, and apparatus employed, determine the precise range of voltage over which this equality extends.   No other factor has been found to modify this equality of absorption.

Perhaps the most convincing proof of the reality of the constancy of the ratio S/P in the filtering and scattering experiments is the close connection which has been demonstrated between these phenomena.   On apparatus I and II the conditions favourable to initial horizontality in the filtering experiment are those of a point on the horizontal portion of a scattering curve.   No chance compensation effects could be related thus.   Yet on apparatus III no horizontality has ever been found in a filtering experiment. This seeming discrepancy can best be removed by assuming that the initial equality of absorption on apparatus III is real but so small that however thin a sheet of a solid absorber is used too big a percentage of radiation is absorbed for this to show.   Absorption by air (if practicable for purposes of measurement) would almost certainly show this equality of absorption.

There is no doubt that the most important part of this work has been the determination of the systematic differences between the results as obtained on different sets of apparatus.   This is consistent with the apparent discrepancy of results obtained by different workers in this laboratory, who have used different sets of apparatus under different conditions.   This is the first time that a systematic investigation has been carried through into this most important point.   Careful attempts have been made to isolate the portion of the apparatus which is effective in producing these differences. The transfer of the various parts of the apparatus (tubes, scatterers, apertures, ionisation chambers) proved that none of these was the effective factor.   The only other considerations are, (a) the configuration of the screens and (b) the actual location of the apparatus in the laboratory.   The former is unlikely since there seem to be no details of configuration which are common to apparatus I and II and absent from III.   The latter consideration arises from the fact that apparatus I and II are in the same room on ground level, whereas III is in another section of the building partly below ground level.   An apparatus of similar dimensions and configuration to apparatus III has recently been built in the same room.   It has not been used by the writer but has given results which agree with apparatus III and not with I or II.   The idea that the actual location is of importance is admittedly an unlikely one, but it is the only remaining difference which appears to be of significance.   If one complete apparatus could be transferred from one room to another, the repetition of the experiments described above would solve this problem.

The above work makes it clear that while the present

theories afford a fairly adequate explanation for experimental findings with homogeneous radiations, they do not account for the results obtained from experiments with heterogeneous X-radiation.

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