THE SCATTERING OF ALPHA PARTICLES

BY CARBON

A thesis submitted to the Faculty of Graduate Studies and Research at McGill University,in part fulfilment of the requirements for the degree of Doctor of Philosophy

by

Laurence R Walker,B.Sc.

The Macdonald Physics Laboratory
McGill University
September,1939

FOREWORD AND ACKNOWLEDGEMENTS

In view of a revival of interest in nuclear physics at McGill and in anticipation of the building of a cyclotron,a program of construction of auxiliary apparatus was started in 1936,in which the writer took part. Delays in the progress of the cyclotron scheme led to the suggestion that some project be undertaken using naturally radioactive sources. The appearance of the work of Bohr on the nature of nuclear reactions indicated that the scattering of alpha particles by the light nuclei might be expected to provide more immediate information concerning nuclear structure than had hitherto been supposed. These considerations led the writer to select the large angle scattering of alpha particles by light nuclei as a subject for experiment. The work was made possible and at the same time limited in duration by the rental of 250 milligrams of radium bromide by the department.

Using a scattering chamber filled with hydrogen at 10 cm. pressure,designed to permit the counting of alpha particles scattered through angles up to 158°,the number scattered into a given solid angle has been compared with the corresponding number from a gold target Assuming that the latter obeyed Rutherford's law of scattering,the departures from this law in the case of the light elements could,thus,be found. The design of the box and the experimental arrangement was such that in many cases the number of particles to be counted was low;this fact, with the necessity of using targets of uniform flatness,rest-

restricted the elements for which it was possible to obtain really satisfactory results to two;carbon and oxygen. These fortunately belong to a class of elements to which the theory in its present form may fairly be applied Moderately extensive results were obtained for boron which were felt to be doubtful for low energies. Beryllium,fluorine and aluminium were examined at a few points.

Clear evidence was found in carbon and oxygen for the existence of resonance levels in the compound nuclei formed and it was possible to draw from the data some conclusions regarding the angular momenta of these excited states.

Because of the extent to which apparatus had to be constructed, not only in connection with the scattering chamber and detecting equipment,but also for the housing of the radium supply and,since, in order to avoid trouble from contamination,it was necessary that the manufacture and the use of sources should be in the hands of different people,it was felt that two men ought to work together on the problem. Mr.A.J.Ferguson has,thus,been a collaborator throughout the course of the work. The preparation of the sources was carried out by him and the measurements at the scattering chamber were made by the writer. This arrangement was followed in the experiments on oxygen which Mr.Ferguson is reporting elsewhere, as well as in the work described here.

. ...

The writer wishes to express his indebtedness to Dr.J.S.Foster for the support which he has given this work;he wishes also to thank Dr.A.Norman Shaw,Director of this Department,for his interest and for assuring the aid of the Department to the project

Dr.F.R.Terroux gave invaluable assistance in doing most of the glass blowing for the radium plant;Dr.W.H.Watson lent much time and advice in connection with the production of certain targets; Dr.C.A.Horton kindly performed a spectrographic analysis of some of the targets;we are indebted to Mr.K.G.Mackay for the use of a scale of sixteen circuit which he had built. A large number of individuals and firms have given us materials,advice or cooperation;we are particularly grateful to the Acheson Colloids Corp. for their interest and advice and to Mr.John D.Leitch of the Eldorado Radium Corp. for his cooperation in connection with the radium rental The writer is grateful to Messrs.Pye,Taylor,Tweeddale and Amesse of the Laboratory staff for technical assistance.

Very grateful acknowledgement must be made to the National Research Council of Canada for their award of a Bursary,Studentship and Fellowship during the course of this work and also to the McGill Delta Upsilon Memorial Scholarship committee for an award.

TABLE OF CONTENTS

INTRODUCTION

The observation by Geiger and Marsden(1909) of the abnormally large number of alpha particles scattered by heavy elements through a large angle led Rutherford(1911) to suppose that the positive charge of the atom was concentrated in a small region at its centre, while the negative charge occupied roughly atomic dimensions(10^{-8} cm.) It was then possible to show that the behaviour of charged particles in scattering would depend only upon the intense field due to the positive charge,the negative charge producing a small effect only at small angles of scattering Then using a model in which the scattered and scattering nuclei appear as point charges,interacting at all distances by means of Coulomb repulsion,Rutherford calculated by Newtonian mechanics the number of incident particles scattered through various angles. The result of this analysis showed that the number of particles $\sigma(\theta)\,d\omega$ scattered per unit time through an angle θ into a solid angle $d\omega$,when one incident particle crosses unit area per unit time and falls upon a single scattering centre,is given by

$$\sigma(\theta)\,d\omega = 2\pi\left(\frac{zZe^2}{2mv^2}\right)^2 \operatorname{cosec}^4 \theta/2 \; d\omega$$

Here z , Z are the charges of the nuclei involved, e the electronic charge, $\frac{1}{2}mv^2$ the energy of the incident particle. This treats the scatterer as being of infinite mass. If this is not the case,the above result holds in a coordinate system in which the centre of gravity of the two masses is at rest and m is taken to be the reduced mass $\frac{M_1M_2}{M_1+M_2}$, where M_1 and M_2 are the nuclear masses

The validity of this formula for elements heavier than aluminium was established in a number of experiments(Geiger,1911;

Geiger and Marsden,1913) However,it was shown by Rutherford(1919) that in the case of hydrogen there may be wide departures from the law (1) and this was confirmed and extended by Chadwick and Bieler (1921),who found that at high energies the observed scattering might be 100 times its expected value,while much smaller excesses were found at low energies These effects were seen as indicative of a departure from the Coulomb law of force for sufficiently close distances of approach. Bieler(1924) also worked with aluminium and magnesium;in this instance the two metals gave very similar results,with both showing a fall below Rutherford scattering at angles of 100 .Rutherford and Chadwick(1925) pursued this work with much the same result.

The very light elements,hydrogen,deuterium and helium,have been the subject of extensive work. Helium has been examined by Rutherford and Chadwick(1927),Chadwick(1930),Wright(1932),Mohr and Pringle(1937) and Devons(1939);hydrogen and deuterium by Rutherford and Kempton(1934),Pollard and Margenau(1935) and Mohr and Pringle (1937). Riezler(1935) has investigated the scattering from neon, and from oxygen up to 5.3 mev. and at relatively small angles ($90°$) Neon showed no trace of an anomaly,but with oxygen it was found that the scattering fell below normal at 4 mev and decreased continuously with increasing energy Two papers have recently been published dealing with the scattering from various gases at angles in the neighbourhood of $90°$ The first is by Brubaker(1938) who has examined oxygen,neon and argon and,more recently (1939),nitrogen The anomalies found in neon and argon were in fair agreement with Riezler,showing only decreases from normal scattering;an interesting feature of the results for neon was the presence of a very sharp dip in the scattering curve only a few hundred kilovolts wide. Oxygen was examined by Brubaker at several angles,with results agreeing with those of Riezler at small angles. At larger angles (110°) the anomaly rose rapidly with increasing energy,rising to about 5 at 6.0 mev.A point of inflection in the curve at about 5.6 mev. indicated the possible beginning of a resonance peak. Devons' work covers oxygen,fluorine,nitrogen,carbon and neon By using energy intervals of 200 kev at which to make observations and keeping the energy spread of each point down to 100 kev he was able to reveal some finer features which previous work had missed. The results for oxygen were in fair agreement with those of Brubaker, being rather extensive in a region where the latter had few points The marked decrease below Rutherford scattering was confirmed for 90° and for low energies The work on fluorine and nitrogen gave clear indications of resonance levels. The results on carbon will be considered in the discussion of those obtained here.

Some years ago,Riezler(1932) examined the scattering through very large angles from various solid targets. His work covered boron, carbon,beryllium and aluminium up to angles of about 155° in the laboratory system. He measured the variation in the scattering with angle between 127° and 155° degrees at the highest energy available, which was about 7.3 mev and in all cases except that of beryllium he measured the variation with energy at the largest angle. With Be, B,C the general variation with angle was the same in the three cases:the scattering rose from a value,perhaps twice normal,at 127° to 43,25,10 times normal respectively.With aluminium the ratio started at 0.5 fell to 0.4 and rose to 1.8 at the largest angle.The yield from boron at the largest angle rose monotonically with the energy,but in the case of carbon passed through a maximum at about 5.8 mev

From the observations of earlier workers and the suggestions of theory one expects that the departure from Rutherford scattering will be greatest at large angles of scattering,at the highest energies and from the lightest elements The last two factors enter since one assumes that the anomalous scattering has its origin in the penetration of the alpha particle into regions in which the inverse square law does not hold.From classical considerations the closest distance of approach or on wave mechanics the probability of finding the nuclei at a small distance from one another would be least and greatest respectively for high energies and small atomic numbers The factor corresponding to the angle effect has its origin in the fact that the partial waves in the expansion of the scattered wave all have their maxima at the greatest angle These facts imply that the greatest anomalies are to be looked for where the classical scattering is least. A further difficulty in examining the large angle scattering is that the range of the particles which have been scattered is very small and becomes smaller with the atomic number. In order that they may be able to reach a detector and still be registered the thickness of material through which they can travel is limited and this implies that the effective thickness of the target is small. Since the anomaly is likely to be a rapidly varying function of energy,it is clear that an arrangement which gives a useful number of particles at one point may be quite unworkable at another

Scattering experiments may be compared on the basis of the following factors:geometry,type of target,counting system and method of comparison with classical scattering Good geometry requires that the angular spread of the incident and scattered beams be small and can really only be attained where the yields are great enough to warrant cutting down the solid angles involved This difficulty may be met in the case of gases fairly easily,by using an annular ring of the gas as a target or by using an annular detector,hence increasing the solid angles without losing definition A similar method was applied to solid targets by Riezler,but,at large angles there are other disadvantages connected with inhomogeneities of the incident beam.

Gaseous targets have the advantage that the number of scattering centres is readily found from the pressure of the gas and examination of narrow energy bands is readily possible. For solid targets it is clear that only a certain definite thickness of the target can contribute to the observed scattering,since alpha particles scattered below this depth have not the energy to come out again Thick targets are,thus,as useful as thin,since the latter need to be supported on some base which must not be able itself to scatter through the thin layer.Used,as was done by Riezler,without further development,the thick target method suffers from the flaw that the effective thickness may be relatively great and give rise to a large energy spread amongst the particles scattered.

The scintillation methods of counting,originally used in this work,had some virtue,in that the scintillation screen could be made a wall of the scattering chamber and,hence,particles with ranges right down to the limit of visibility might be observed Recently ionisation chambers and proportional counters have been commonly used for detection. The former,used by Mohr and Pringle and by Devons gives a low ratio of pulse height to gamma ray background,but,this is compensated for by the uniformity of the former. The latter has been used by Wright,Pollard and Margenau and by Brubaker and gives a better discrimination against the background, while giving alpha particle pulses of various sizes Riezler(1935), in his second paper,somewhat surprisingly used a Geiger counter, with its attendant high background,on the grounds that the proportional counter had a narrow counting region at low pressures There does not seem to be any justification for this belief.

In much of the work on gases it has been customary to suppose that below a certain energy the scattering in some standard gas is normal and to use the gas in these conditions for comparison.Pollard and Margenau made such an assumption about deuterium and Devons and Brubaker treat the argon scattering below 5mev as normal. Gold has also been used for comparison and its high atomic number should make Rutherford scattering fairly certain in the energy range used

Early investigations were principally concerned with the problem of determining the nature of the nuclear field and after the advent of wave mechanics they were seen as giving information about the height and penetrability of the potential barrier The ideas of Bohr(1937) which asserted that every nuclear reaction takes place through the formation of a compound state with the subsequent emission of another particle served to show scattering in a new light. For here it appears that scattering is simply one of several competing processes in which it happens that the same type of particle is re-emitted.Thus,scattering experiments,even as those on disintegration,give information concerning the nature of the compound nucleus. In particular we should expect to find the same signs of resonance entry into the excited states of the compound nucleus as are revealed in the excitation functions for the disintegration processes.Having assumed such a mechanism for the nuclear reactions,it is possible,as has been done by Breit and Wigner (1937) and Bethe(1937),to calculate cross sections for the various nuclear possibilities The detailed interpretation and evaluation of some of the quantities appearing in such a formula,such as the matrix elements for various transitions and the widths of levels in the compound nucleus,is not possible for theory in its present state,but the general form of the cross sections derived and their angle and energy dependence are doubtless independent of special assumptions.An examination of the formula shows that the magnitude of resonances and,indeed,their appearance or non-appearance will be sharply dependent on the angle of scattering. Except in purely accidental circumstances resonances must appear at 180° and have their maximum amplitude there The latter will increase with decreasing atomic number,with increasing energy and with the angular momentum of the compound state. In an attempt,therefore, to find resonances in the scattering process it was felt best to work at as large an angle as possible.

APPARATUS

The design of the scattering box was determined by the following considerations:it was important to be able to count particles of very short range;the geometry must be such that the angular spreads were as small as possible consistent with obtaining a useful yield at points where the anomaly was low;it should be readily possible to change from one angle to another;the arrangements should be such that during the course of a run it is possible to go from the element under consideration to a gold target and back In the light of subsequent experience it appears that the third point might have been sacrificed to the object of having a larger target.

In view of the fact that in large angle scattering the positions of the source and the detector are contiguous it is very important to take advantage of the methods worked out by others for the detection of heavy particles in the presence of strong gamma radiation. The type of proportional counter consisting of an axial wire in a cylinder,the latter being made negative with respect to the wire,was chosen to be used with a four stage linear amplifier. The counter was used without window in order to count particles of low range and the source holder,target and counter placed in one scattering box filled with hydrogen at a low pressure, Hydrogen is the inevitable choice for filling the box since the gas has to have a low stopping power,give a low gamma ray background compared to the size of alpha particle pulses,give rise to no counts because of its ability to scatter alpha particles into the counter and,finally,be not itself scattered into the counter

In order that the incident alpha particles should fall upon the target in a fairly homogeneous group the target was made to stand normal to a plane containing the source,the counter and the target,the particles,thus,travelling normally through the window of the source holder The counter was held fixed while the source was swung about an axis passing through the target face;the target itself was so constrained to move that a normal to it always bisected the angle between the counter and the source This latter arrangement prevents any undue absorbtion of the incident or emergent beam in the target itself at any angle. The target was designed in such a way that it had two faces,which could be made to replace one another in space,one face being of the element being concerned, the other of gold The targets in all cases consisted of thick layers of the element.

Figs.3,4 and 5 show the disposition of the scattering box and its contents.The components are mounted on a 3/8" brass plate with a flange running round it A 1/8" neoprene gasket is placed on this flange and the lid of the chamber rests on this having a shoulder near the lower edge of its sides to space it when the gasket is compressed.The base plate is supported by three stout brass pillars. The lid of the chamber consists of five pieces of brass sheet,screwed and soft soldered together,with an observation window in the top sheet The leads to the amplifier and to the high voltage outfit are carried through the base plate by means of hard rubber plugs waxed into the base;the plug carrying the power line has inlaid sulphur rings on either side to eliminate surface discharges.The lower shoulders of these plugs are arranged to take grounded brass cylinders which shield the actual connections between the shielded leads and the carry-through connections.

The arrangement of the target assembly can be seen from Fig.3

where it is shown at B By means of the gear train, rotation of the shaft carrying the target through any angle causes the rotation of a concentric shaft carrying the source arm through twice that angle. The driving shaft passes through the base by means of a ground joint and the source arm shaft is free to rotate about it A third shaft, concentric with the driving shaft, may be rotated independently and communicates its motion by means of another gear to the target holder; by means of a spring stop mounted externally this shaft can be permanently set in two positions 180 apart. Since the axis of the target holder is offset from the axis of the driving shaft the two faces of the target can be brought successively into the desired position. The layers of material forming the target are 3.0 cm. by 3.2 cm. and mounted on a brass block 1.0 cm. thick The latter is held in place on its holder by three pins.

The source holder consisted of a lead block shown at A, 2.0cm. square and 3.3cm. deep. A hole is drilled right through this, 1.0cm. in diameter at the back, 0.5cm. in diameter in front, the transition being made by a slight taper and a shoulder near the front This shoulder served to hold in position a brass cylinder, 0 8cm. in diameter, into the front of which the source button was screwed. The latter was 0.5cm. in diameter and turned out of nickel rod The brass cylinder was threaded right through and served as a holder for the source button. The back of the lead block is closed by means of a small brass plug which could be waxed into place, while the front is covered with a piece of mica, held in place by a small brass ring and wax. The stopping powers of the two windows used at different times were 0.65cm. and 0.72cm. From the side of the source block there is a 1/8" pumping outlet, which was connected to a separate pump line through the bottom of the box,originally by means of rubber tubing and later by a copper tube.The source holder which was repeatedly removed was located by two pins in its base fitting into two holes in the source arm. The holder and the scattering box were pumped out in parallel,a charcoal trap immersed in dry ice and acetone being placed in series with the holder to take up radon from the source button;a cross manometer between the two lines ensured that the difference of pressure across the mica window was kept small A tapered collimating tube,G,was used to define the alpha particle beam constructed of celluloid. The edges of this tube were so disposed and shaped that no particles could be scattered from them into the counter That this was the case was established by leaving the counter open in the direction of the collimator,but closed in the direction of the scattered alpha particles No particles were observed Between the lead block and the collimator were placed the mica screens for reducing the initial alpha particle energy.A further strip of 1/8" lead,not shown in the drawing,closed the space between the holder and the collimator The two other open sides of this gap were also closed after everything was in place. There should be in this assembly,no scattering from anything but the target and this has been found to be true.

By means of two further concentric ground joints in the top of the box to which celluloid screens,H and I,were attached it was possible to close off the collimating tube in order to make a background count or to place a screen in front of the counter to ensure that no particles of abnormally large range were entering and also to facilitate proton counts where these had to be taken. A rack,J,standing on the base of the box,immediately in front of the counter,accomadated screens for selecting the particles admitted to the counter

In cases analogous to the present,there are suggestions in the literature that a magnetic clearing field between the target and the counter to remove the secondary electrons generated in the target by the gamma rays is a desirable thing.We therefore arranged originally to have pole pieces built into the lid and base in the desired position and to run an electromagnet on to these poles after the box was closed. The electromagnet is shown in Fig.6. The field strength in the gap was about 1500 oersteds In operation, however,we found a distinct increase in the background of the counter when the field was switched on,quite independently of its direction. This could not be attributed to any disturbance from the power line of the magnet since it was not present in the absence of a source It seems reasonable to suppose that the magnetic field lengthens the paths of the ions in the counter and,thus, reduces its breakdown voltage or increases its multiplication factor. Removal of the target made little difference to the background and one can conclude that very little of the latter arises in the target.

The counters used in the scattering box were developed in an effort to combine ease of construction with as low a capacity for producing secondaries under gamma ray bombardment as possible. Counters of the rather massive type developed by Duncanson and Miller(1934) in which the strongest field is in the neighbourhood of several steel balls were tried,but found to have a very high gamma ray background and an unnecessarily high running voltage.Wire counters,with the wire terminated by a steel ball to prevent discharges,were found to be more convenient and to have a diminishing gamma ray background as the amount of material used in their construction was diminished;a process which could be carried quite far in this case since the counter was not expected to stand any difference of pressure. In addition,some troubles with hard rubber as an insulator led to the substitution of paraffin. The counter shown in Figs.3,4 and5 met the requirements quite well. The anode is a piece of .005" steel wire,3.5 cm. long,soldered into a small brass plug at one end and having a 1/32" steel ball soldered to the other. The cathode was of 2 mil brass sheet wound into a cylinder 2.0 cm. in diameter and 5.0 cm. long. To this was soldered a front of 5 mil copper with an opening 0.8cm. by 1.4cm. Care was taken to avoid having much solder within the counter itself The insulation at the back of the counter also supports it and consists simply of a rectangular slab of paraffin.The whole counter has considerably rigidity despite its lightness. They are easy to replace when contaminated and if manufactured with new materials and tools kept for the purpose have less than 1/2 count per minute for background when new

The high voltage supply for the counter was obtained from a compact power outfit designed to give small currents up to 6500 volts,using a 5500 volt R.M.S transformer and two 866 rectifier tubes When the power outfit was built the use of voltages as high as 4500 on counters was contemplated and a voltage control circuit was designed with this in mind An adaptation of the neon tube circuit of Gingrich(1936) has been utilised. The voltage to be stabilized is applied across a bank of 100 small neon tubes in series with 5 megohms The peculiar form of the voltage-current characteristic of the neon lamp supplies the controlling action while the tubes are tapped off in sets of ten and some singly to act as a potentiometer.Another potentiometer across three 45 volt

B batteries provides fine control over the counter voltage. The control is moderately satisfactory,although for the range of counter voltages actually used,which are in the nighbourhood of 1100 volts,a vacuum tube circuit would be preferable A resistance-condenser filter circuit is placed between the control and the counter to eliminate high frequency oscillations which are present.

The linear amplifier used has been constructed quite without changes from the circuit described by Dunning(1934) This is a four stage resistance coupled amplifier intended to give an amplification of about 10^5 to 10^6 without distortion. The frequency response of the amplifier was measured to see that it was flat for frequencies corresponding to the time constants of the pulses it was to count and it appeared satisfactory for the purpose. In operation the biases were arranged in order to give a good plateau on the characteristic of counts versus voltage from a gold scattering experiment. The system was free from all but an occasional and infrequent violent electrical disturbance in its neighbourhood

During the progress of all runs the output of the amplifier was put on the screen of a cathode ray oscillograph,so that the state of affairs in the box could be quickly appreciated. Originally the recording of the counts was effected with a Cenco high impedance counter and a single thyratron circuit,also taken from Dunning's article.It became apparent after a number of runs had been taken that the counting rate from gold was too great for the single tube and it was replaced by a scale of sixteen circuit. In order to preserve the few runs which had been made the old outfit was calibrated against the scale of sixteen:the plot of the logarithm of one rate against the logarithm of the corresponding rate of the other gave the expected straight line corresponding to a fixed resolving time for the single tube

With the intention of recording some of the alpha particle pulses photographically an oscillograph of the type described by Shire was constructed The construction presented some difficulties,the principal of which was that of obtaining iron-free aluminium for the moving element However,this was accomplished and the instrument was used to obtain some records. These records resembled superficially what was seen on the screen of the cathode ray oscillograph,but an examination of the kind of pulses being fed to the oscillograph by its associated amplifier showed that these were distorted to several times their natural length. Faster pulses produced only very small kicks of the oscillograph,indicating that the time of response of the instrument was far greater than that calculated in the design. This was in all likelihood due to the magnetic field being too low. Since other far more attractive methods of recording were at hand no attempt was made to improve the oscillograph.

In order to vary the energy of the incident beam mica screens were placed in its path. All the mica was split under sodium light to ensure its uniformity. In addition to the mica screens we have used artificial screens made by casting solutions of celluloid in amyl acetate on glass. This was necessary since the screens used in front of the counter to cut down the scattered beam were 1.5cm. by 2.0cm. and needed to be made in thicknesses down to 1mm. stopping power The stopping power of all screens was measured by interposing them between a fresh polonium source mounted on a travelling carriage and a fixed counter closed by a window of 0.8cm. stopping power The number versus distance curves,with and without the screen, were obtained by making the appropriate counts and correcting for the inverse square law. From the pair of curves the stopping power of the screen could be evaluated

The sources used in these experiments consisted of the active deposit collected on a nickel button during a 2 1/2 hour exposure to radon. The alpha particles whose scattering is observed are of course those from Radium C'. The 250 mgm. of radium bromide were stored in solution in a distant part of the building.From this solution it was possible to remove by means of Toepler pumps about 200 millicuries of radon for source making purposes. In the manufacture of sources the radon with its impurities was brought by the pumps to a purifying chamber which employed the usual chemical means to remove hydrogen,oxygen and carbon dioxide. When inert gases were present the radon was condensed with liquid air and the gases pumped off The radon was then forced into a small space at the bottom of a glass taper which held a brass ground joint;the source button was screwed into the latter A field of about 600 volts was then put across the space. After a source had been made an oxygen-hydrogen mixture,prepared by electrolysis,is admitted to enable the radon to be pumped back to the radium bulb The loss of radon in this procedure was so small that the apparatus could be made to give 5 sources per day for several days in succession without appreciable loss of strength. The strength of most sources lay between 35 and 45 millicuries. Before being put into use the strength of the source was measured with an electroscope although a knowledge of the strength is not necessary. The procedure of pumping back the radon and measuring the source takes about twenty minutes so that the Radium A has decayed by the time these operations are complete.

In order that one may calculate with any certainty the actual number of scattering centres in the scattering from a solid target the path of the alpha particle from entering to leaving the target must be well known. Assuming a perfectly plane target and the arrangement of these experiments,it is clear that the distance travelled into the target is equal to that travelled coming out.If the surface departs from a plane there will be a difference between these distances and this difference leads to the effective scattering depth being different at different points of the target Presumably the effective depths would be distributed evenly about the value for a plane surface,but it is likely that the total scattering will be greater than is expected since particles very near the end of their range might contribute heavily,if the point is one at which the scattered particles can escape easily. If the two distances are to be nearly equal we can see that a normal to the surface must not depart by more than about 10 from the normal to the target ,for many points on the surface,

In the work on carbon we used three small plates of spectroscopically pure carbon cut from rods and buffed on filter paper As a check on the results found with this target,another was made by painting layers of "Aquadag" on a hot Pyrex sheet, then heating strongly to destroy the protective colloid. This target was also buffed. There seemed to be no significant difference between the two results. A boron target prepared in the same manner as Riezler's could hardly be considered satisfactory. Boron was ground to as fine a powder as possible,mixed with amyl acetate and made into a block on a brass base,the surface then being smoothed out This target exhibited specular reflection at a few degrees,but,a microscopic examination showed it to be rather badly pitted The boron used was pure amorphous boron (Eimer and Amend) which was examined spectrographically and found to contain a few per cent. of magnesium and silicon,but,not enough to warrant rejecting it. Satisfactory targets were made of beryllium and of lithium fluoride,for the examination of fluorine. The beryllium was prepared by the evaporation of the metal upon a copper base;the layer,thus obtained was removed from the copper and found to possess the polish of the latter.The layer was 2×10^{-3} cm. thick. Lithium fluoride was found to be pure spectroscopically. It was fused in a platinum crucible and poured into a steel dish;the resultant mass of small crystals was quite robust and could be cut and polished Targets of aluminium and copper were occasionally needed and these were available in pure sheets. The gold used throughout was .002" pure gold sheet.

OPERATION

Since circumstance impelled us to use hydrogen as the counter gas it was necessary to find pressures at which it gave good discrimination between the alpha particles and the gamma ray background. It was found that the discrimination improved steadily as the pressure was raised from 4cm. to over 10cm. of mercury The value of 12cm. of Hg. was thus chosen as a compromise between low stopping power and good discrimination. When the hydrogen was kept pure the running of the system appeared to be stable and free from spurious discharges The presence of water vapour or any organic vapour in the scattering box cause a remarkable "softening" of the counter.

The normal operating voltage of the counters was in the neighbourhood of 1100 volts, varying somewhat from one to another. Since the output voltage of the alpha particle pulses from the amplifier is given by the product of the multiplication of the amplifier by that of the counter times the size of the initial pulse, it is plain that in order to be registered this product for a given alpha particle must exceed a given value. By setting the multiplication of the amplifier at a certain value we arrange that all pulses below a certain limen are not registered. If we suppose that an assortment of alpha particle pulses of different sizes are arriving together with a gamma ray background, it is apparent that as we increase the voltage on the counter and, consequently, the multiplication the voltage limen will descend and the number of registered counts should increase, reaching a constant when all the alpha particles are being registered and remaining at this value until the gamma ray background begins to be picked up. Some runs were taken to count the number of alpha particles scattered from gold as a function of the voltage The results as might have been expected depended to some extent on the strength of the source, for this determines the height of the gamma ray background. Under such different circumstances the plateaux were found to vary from about 75 volts to over 200 volts. It is possible that in the case of some of the strongest sources a few of the alpha particles may have been lost below the gamma ray background,but the evidence is that this number was very small From what data there is on the variation of the multiplication factor in a proportional counter,that the plateau will be widest when a relatively low voltage is used on the counter and the amplification is derived from the amplifier seems a reasonable conclusion

In the operation of the scattering box one of the most important matters is the avoidance of or recovery from radioactive contamination All sources before being put into the chamber were given a short outgassing by heating in vacuo;the extent of this outgassing seems to be rather critical since underheating leaves an appreciable quantity of radon on the source while too drastic treatment results in the loss of some of the activity. Originally,thin artificial windows made from Duco cement solutions in acetone were used to close the source holder.These proved to be extremely pervious to radon and could not be used with the most strongly heated sources. When these were replaced by mica,contamination slowly grew in the counter after making no appearance for perhaps twenty minutes. This was traced to the diffusion of radon through the 1.5mm. walled rubber tubing connecting the source holder to the pump line. With the removal of this and the use of the trap mentioned above progressive contamination was avoided. To avoid initial contamination it was customary to remove the source holder and insert the source at some distance from the box;the source holder was then replaced in the box with a strong fan blowing across the operations.By these methods the backgrounds were kept down to less than 1 per minute.When the background rose over 2 per minute the run was generally abandoned. When the box became contaminated it was opened up and the fan allowed to blow over it for about an hour; persistent contamination was dealt with by removing the paraffin which covered the inner walls of the box and replacing it with new material and also by washing the counter in dilute nitric acid.

The procedure in taking runs which was followed with very few changes throughout was as follows:first,a 2minute background run;then,1 minute with the gold,10 minutes with the unknown, 1 minute with the gold,2 minutes on the background and through the same cycle repeatedly,generally extending the gold runs as the source decayed.In this way the initial gold count would lie between about 300 and 1400 per minute. Runs were halted when the count from the unknown fell to 4 per minute or when the background rose to 2 per minute. Occasionally a short run would be taken with the movable screen in front of the counter to verify the absence of extraneous particles or in the case of boron the presence of protons.

ANALYSIS

The analysis of the results has as its object the evaluation from the observed data of the ratio of the measured scattering from the unknown element to the scattering to be expected if Rutherford scattering took place. It is first necessary to calculate the number of particles to be expected from the gold and from the unknown (in future, labelled X) This may be done using a convenient formula due to Darwin(1914) which states that q the number of alpha particles scattered into angle ω, through an angle ϕ, when Q particles per second fall on a layer containing N scattering centres, is given by

$$q = QN\omega\left(\frac{zZe^2}{2MV^2}\right)^2\left\{\operatorname{cosec}^4\frac{\phi}{2} - 2\left(\frac{M}{m}\right)^2 + \left(1-\frac{3}{2}\sin^2\phi\right)\left(\frac{M}{m}\right)^4 + \cdots\right.$$

where $\frac{MV^2}{2}$ is the energy of the alpha particle, Ze is the nuclear charge, m the mass of the scattering nucleus This formula holds good in the laboratory system of axes and takes account of the reduced mass In the case where the alpha particle penetrates into the target and loses energy in so doing, we write N as nt and replace $\frac{t}{E^2}$ by $\int_0^{x_0}\frac{dx}{E(R_0-x)^2}$, where x_0 is the maximum depth of penetration In calculating the penetrations we shall find it convenient to work with the air ranges of the alpha particles. From the definition of stopping power, we have the relation $N_x\sigma dt = 2N_A dt_{air}$ where N_x is the number of atoms per c.c in X and N_A is the number per c.c. in air, or, alternatively, $\int\frac{N_x dt}{E^2} = 2N_A\int\frac{dt_{air}}{\sigma E^2}$

The ratio of the Rutherford scattering in gold to that in X is now seen to be

$$\left(\frac{Z_{Au}}{Z_x}\right)^2 \times \frac{\operatorname{cosec}^4\phi/2 - 2\left(\frac{M}{m_{Au}}\right)^2 + \left(1-3/2\sin^2\phi\right)\left(\frac{M}{m_{Au}}\right)^4}{\operatorname{cosec}^4\phi/2 - 2\left(\frac{M}{m_x}\right)^2 + \left(1-\frac{3}{2}\sin^2\phi\right)\left(\frac{M}{m_x}\right)^4} \quad \frac{\int_0^{x_{0,Au}}\frac{dt}{\sigma_{Au}E^2}}{\int_0^{x_{0,X}}\frac{dt}{\sigma_{Au}E^2}}$$

In the case of the light elements and over the short ranges of the integrals there we may treat σ as a constant and take it outside the integral.

At the same time we may suppose the range-energy relation to be linear over such a small interval and if this is the case it is easy to show that the integral becomes $\frac{x_0}{E(R_0)E(R_0-x_0)}$ where x_0 is the limit of the integral and the maximum depth of penetration. In the case of gold where the penetrations are great and the variations in the stopping power considerable, neither of these simplifications is possible and it is necessary to tabulate the integral

The integral which we need is $J=\int_0^{x_0}\frac{dt}{E(R_0-t)^2}$ and we are given the range-energy data of Rosenblum(1928) on the energy loss of Thorium C' alpha particles, which we may write as $E=y(x), x=A-R$, where x is the thickness of gold in mgm./cm^2, R is the range of the alpha particle and A is the range of the Thorium C' particle. We may now write $J=\int_{x_1}^{x_1+x_0}\frac{dt}{y(t)^2}, y(x_1)=E_0$. Let us now put $I=\int_0^{x_1}\frac{dt}{y(t)^2}$, we then have $J=I(x_1+x_0)-I(x_1)$

It is, thus, convenient to tabulate $I(x)=\int_0^{x}\frac{dt}{y(t)^2}$

In order to evaluate this integral Rosenblum's data were plotted and values taken off at intervals of 0.4 mgm./cm^2. By means of Weddle's rule the numerical integration was then carried out. The results are shown graphically in Fig.7

The calculation of the maximum depth of penetration in X depends upon solving the equation

$$\alpha E(R-x)=E(x+t)$$

where R is the range of the incident alpha particle at the target, x is the maximum depth of penetration, α is the fraction of its original energy retained by the scattered particle and t is the stopping power(actually the air equivalent) of the hydrogen between the target and the counter face plus the residual range which a particle must have at the face of the counter in order to be registered. An exploration with a polonium source of the behaviour of the counter towards alpha particles grazing the face of the counter indicated that if an alpha particle crossed the face, however obliquely, it was registered. The assumption has, therefore, been made that all the value t comes from the stopping power of the hydrogen. The calculation of the air equivalent of the hydrogen is equivalent to the solution of the equation

$$\frac{pd}{76} = \int_0^t \frac{dx}{\sigma(x)}$$

where $\sigma(x)$ is the stopping power of hydrogen for a particle with air range x, p is the pressure of hydrogen and d is the distance from the counter face to the target. $\sigma(x)$ has not been measured for the lowest energies but its mean value for very low energies is indicated from the data quoted by Mano (1934) on the ranges of alpha particles in hydrogen and in a letter by Rogers (1939). By plotting the values of $\sigma(x)$ obtained from Mano, together with these more tentative points, we may draw a smooth curve from which $\sigma(x)^{-1}$ can be found. By integrating step by step we solve the equation above for t. All the air ranges used in the work were taken from Holloway and Livingston (1938)

There is a similar equation to solve in the case of the gold,

$$\alpha E(x+R) = E(t'-x)$$

here R is the solution of $y(R)=E_0$ and t' of $y(t')=E_1$ where E_0 is the incident energy and E_1 is the energy corresponding to the quantity t above. It is necessary to extrapolate Rosenblum's curve rather extensively to obtain t'. There have been attempts to measure the end point of the curve, but, they are unreliable. By making a series of measurements of the relative numbers of scattered particles from gold at various incident energies it was possible to choose the value of t' to give the best agreement. This was found to be 33.7 mgm./cm^2. It is to be noted that since the work on the gold integral is carried out in mgm./cm^2, the values of the integral taken from the graph must be multiplied by the numerical factor 0.568 in order to be compared with the penetration integrals for the element X.

It will be noted that in the expression for the ratio of the predicted counts in gold and X,we have simply the product of two factors,one of which is independent of the energy and in making a series of runs at one angle the ratio is given by a constant times the ratio of the penetration integrals.

In working out the actual gold to X ratio from the observations it was assumed that the decay of the source during the 10 minute runs on X was linear The total number of counts from X,properly corrected for background,is,thus,compared with the sum of the means of the gold counts,before and after an X run No background correction was necessary for the gold

In the original runs with the carbon,no screens were put between the counter and target so that the energy spreads in any one run were rather considerable (from 500 kev. to 300 kev.) This was atoned for by the fact that it was possible to count many particles and fix the mean value over the interval quite well Recently the device of cutting down the energy spreads by putting absorbers in front of the counter has been tried. When this is done a new value of t comes into use. The lack of any outstanding contradiction between the runs made in the two different ways indicates that the assumptions made in calculating the yield integrals must be fairly reliable.

RESULTS

Measurements were made upon the scattering from a carbon target at three angles;in the laboratory system of reference these were 155°,137° and 112°. In the system in which the centre of gravity of the alpha particle and carbon nucleus is at rest these angles become 163°38′,150°08′and 130° respectively. A principal set of observations was made at each of these angles with initial energies spaced 0.5 mev apart,ranging from 7.10 mev to 4.00 mev. At the largest angle a few other runs were made at different energies. The results of these expeiments are summarized below.The tables below give first the energy spread of the scattered particles;then the sum of the means of the pairs of gold counts and the sum of the carbon counts.If more than one run has been taken at a point the separate runs are added together and the totals shown. The observed ratio of gold scattering to carbon scattering over equal periods is then calculated and entered;beside this appears the expected ratio of gold to carbon scattering if both obeyed Rutherford scattering, which has been arrived at by use of Darwin's expression and by calculation of the penetration integrals. The ratio of the calculated gold to carbon ratio to that observed gives the anomaly at the point. Numerically,this is given in the final column,while all the anomalies are plotted graphically against energy in Fig 9.

Table 1. Angle 155°

Energy range in mev.	Gold	Carbon	Au/C obs.	Au/C calc.	Anomaly
7.10-6.62	315.5 393 606 1314.5	259 360 574 1193	11.01	278	25.2
6.66-6.20	290.5 463.5 276.5 313 1343 5	260 399 212 252 1123	11.95	299	25.0
6.28-5.81	242	242	10.00	286	28.6
6.09-5.65	1102.6 1426.4 2529	1111 1426 2537	9.97	313	31.4
5 73-5.51	507.5	339	14.99	576	38.4
5.57-5.18	1049.6	1008	10.41	319	30.6
5.19-4.81	552.3	260	21.2	338	16.0
5.09-4.83	1327.3	371	35.8	408	11.4
5.09-4.~~83~~ 74	398.2	220	18.1	326	18.0
5.00-4.63	1461.4 352.6 388 2202	562 121 159 842	26.16	337	12.9
4.74-4.40	1252	358	35.0	350	10.0
4.98-4.63	935	297	31.5	337	10.7
4.51-4.18	1966 7	756	26.0	348	13.4
4.54-4.21	559	207	27.0	344	12.8
4.02-3.72	2563.5	283	93.1	381	4.1
3.93-3.63	712	60	118.6	373	3.1

Table 11 Angle 137°

Initial energy in mev.	Gold	Carbon	Au/C obs.	Au/C calc.	Anomaly
7.10	2414.4	783	30.8	254	8.24
6.66	651.1	174	37.4	254	6.80
6.54	1864 1467 3331	486 390 876	38.0	254	6.68
6.09	354 1547.4 1901.4	134 695 829	23.0	256	11.14
5.72	2597	1100	23.6	256	10.84
5.58	2027.7	846	23.95	257	10.72
5.00	1377.1 256 2084.3 3717.4	239 43 404 686	54.2	258	4.75
4.54	115 2119 1184 1417 303 5138	32 254 141 182 44 653	77.2	262	3.39

The energy ranges are shown on the graph.

Table 111 Angle 112°

Initial energy in mev	Gold	Carbon	Au/C obs.	Au/C calc.	Anomaly
7.10	746.6 2752.3 3498,9	160 591 751	46.6	162	3.48
6.66	2062.4	343	60.1	166	2.76
6.09	3684.8 1769 5453.8	281 162. 443	123	170	1.38
5.60	2376	95	250	173	0.69
5.58	1419.2 3825.6 5244.8	43 264 307	171	173	1.01
5.25	3209	125	257	176	0.69
4.51	3607.3 322.5 3929.8	460 40 500	78.6	181	2.30
3.93	1862	100	186	186	1.00

The energy ranges are shown on the diagram.

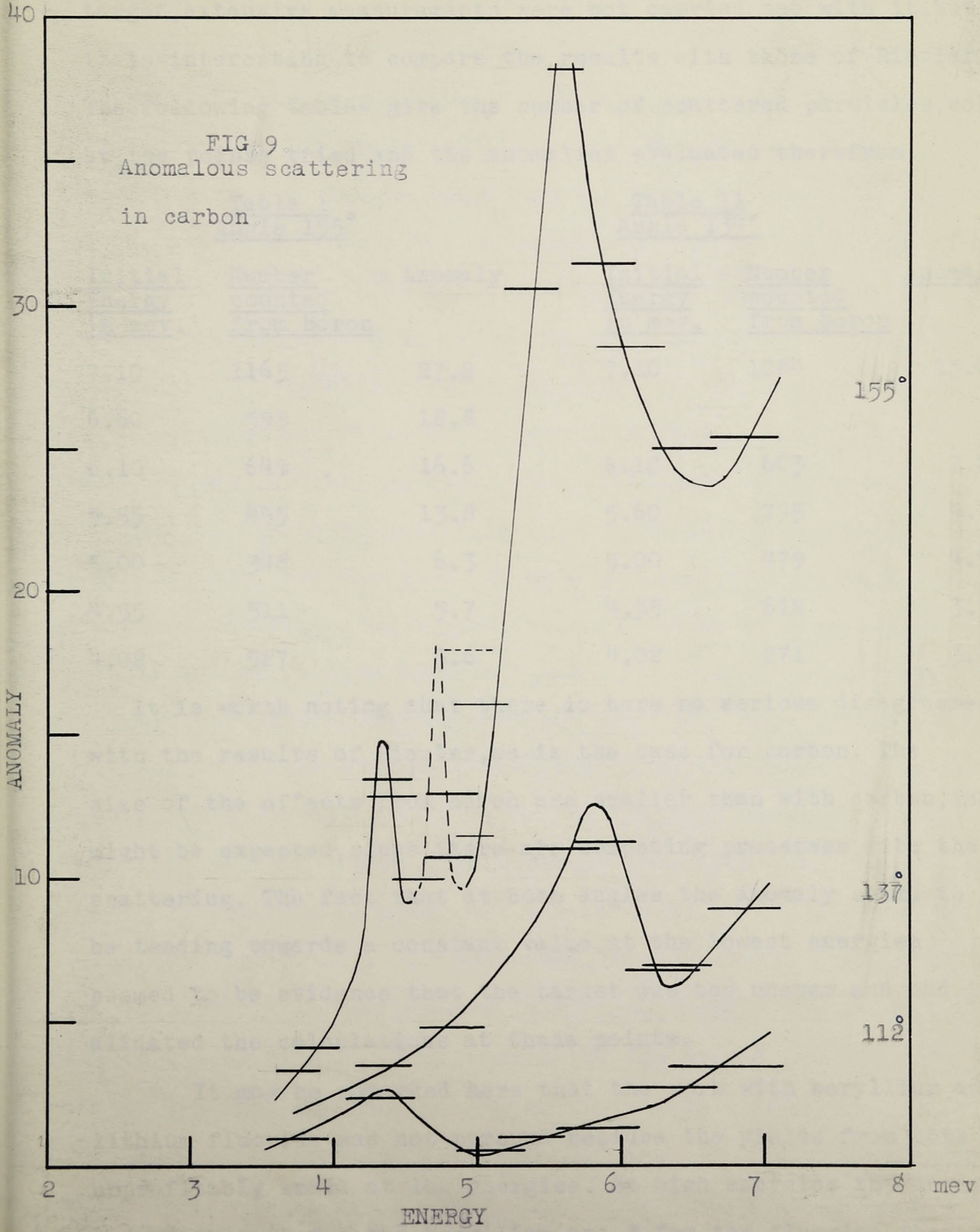


FIG 9
Anomalous scattering
in carbon
40
30
20
10
ANOMALY
155°
137°
112°
2
3
4
5
6
7
8
mev
ENERGY

BORON RESULTS

In view of the somewhat unsatisfactory character of the boron target, extensive measurements were not carried out with it, but it is interesting to compare the results with those of Riezler. The following tables give the number of scattered particles counted at the points tried and the anomalies evaluated therefrom.

Table 1
Angle 155°

Initial Energy in mev.	Number counted from Boron	Anomaly
7.10	1163	27.2
6.60	593	18.8
6.10	649	16.6
5.55	455	13.8
5.00	348	6.3
4.55	511	5.7
4.02	527	5.6

Table 11
Angle 134°

Initial Energy in mev.	Number counted from boron	Anomaly
7.10	1084	15.0
6.18	603	7.0
5.60	795	4.8
5.00	479	4.5
4.55	612	3.9
4.02	271	3.9

It is worth noting that there is here no serious disagreement with the results of Riezler, as is the case for carbon. The size of the effects from boron are smaller than with carbon, which might be expected, since there are competing processes with the scattering. The fact that at both angles the anomaly seems to be tending towards a constant value at the lowest energies seemed to be evidence that the target was too uneven and had invalidated the calculations at these points.

It may be remarked here that the work with beryllium and lithium fluoride was not pursued because the yields from both were unprofitably small at low energies. At high energies the anomaly was roughly 25 for the beryllium and 3 for the fluorine, the latter evidently reflecting the strong effect of competing processes.

DISCUSSION OF THE CARBON RESULTS

It will be noticed that nearly all the runs were made without counter screens in order to increase the yield This means that the energy spreads were rather great and some finer features may have been lost This is compensated for by the knowledge that the mean values over the intervals considered are fairly definitely known The method used to locate the resonance peaks in oxygen by gradually hemming the point into a narrow range were tried in the short time at one's disposal,but,the early results were contradictory and the presence of the resonances had to be detected through their effect on mean values It is rather surprising that the disagreement with Riezler is so great,amounting as it does to a factor two at the large angle It was felt at the start that the method of calculation used here was perhaps unreliable in some unsuspected way.In order to see if this were the case, we made a number of runs to investigate the scattering from copper, which is known to obey Rutherford's law. An agreement with this fact was found within the experimental error,whether or not counter screens were used Some further trials were made with aluminium which had been investigated by a number of workers Here our results,while not in complete agreement with the others,did not depart significantly from them.These facts led us to believe that our methods were not at fault.

There appear to be two resonance levels between 3.50 and 7.00 mev. for the scattering process in carbon. These correspond to excited states of O^{16} . The energies of the resonances are 4.3 ± 0.1 mev and 5.5 ± 0.1 mev and the excitation energies of O^{16} to which these correspond are 10.5 and 11.5 mev. above the ground state. The additional resonance level shown by the dotted line at 4.8 mev would require finer work before it could be considered as established, but, it appears that some such curve is necessary to account for the odd succession of mean values. Two of these levels lie below the top of the potential barrier using Bethe's values, for this is 4.9 mev for carbon. It is possible that the greater apparent width of the upper level is caused by its greater possibility of decay when it lies above the barrier.

Carbon (and oxygen) are fortunate instances of cases where the Bethe dispersion formula takes a particularly simple form. This is due, first, to the fact that the spins of the scatterer and the the alpha particle are zero, hence eliminating from the wave function describing the sytem a large number of terms; secondly, to the circumstance that except at high energies (about 6.5 mev for carbon and still higher for oxygen) the competing processes of neutron and proton emission are energetically impossible. This causes the whole width of the level found to be due to the process of alpha particle re-emission, if the dubious process of inelastic scattering and gamma ray excitation be omitted. Under these circumstance Bethe gives for the ratio of the cross section for scattering to the Rutherford cross section the expression

$$\frac{\sigma(\theta)}{\sigma_0} = 1 + \frac{\rho^2 + 2\rho \sin \zeta + 2\rho x \cos \zeta}{1 + x^2}$$

where

$$\rho = 2(2J+1)\left(\frac{\hbar v}{e^2 z Z}\right)\frac{\Gamma^r_{p_p}}{\Gamma_r}\sin^2\theta/_2\, P_J(\theta)$$

$$x = 2(E - E_r)/\Gamma_r$$

$$\sigma_0 = \left(\frac{e^2 z Z}{2Mv^2 \sin^2\theta/_2}\right)^2$$

J = angular momentum of compound state

$\Gamma^r_{p_p}/\Gamma_r$ = fraction of width level from scattering

E_r = resonance energy

$$e^{i\zeta} = e^{i\alpha \log \sin^2\theta/_2} \quad \frac{1+i\alpha}{1-i\alpha} \quad \frac{1+Ji\alpha}{1-Ji\alpha}$$

For large ρ this assumes the value ρ^2 at its maximum as a function of x. Since ρ is large under our conditions we might hope to deduce a value of ρ^2 and, hence, of J from our work. This will not necessarily be the case, however, for the anomaly due to the resonance will be imposed on another due to barrier penetration and the two add vectorially. We shall evidently only be able to make claims about the upper and lower bounds of the sum of two vectors Evaluating for the two resonances we find the following set of values

j=0	j=1	j=2
1.095	3.28	5.46
1.24	3.72	6.18

Choosing J=1 for the lower resonance and J=2 for the upper we find ρ^{12} to be 10.8 and 38.3 in the two cases;these values are roughly twice as great as the observed difference between the resonance and its surroundings A choice of lower values of J in either case could not account for the facts,but higher values cannot be ruled out Tentatively, then we may suggest that the levels are P and D,respectively;the extra level if it were genuine would also have to be a P level or higher. It is interesting to see that Devons' experimental points also indicate the existence of a resonance in the region of 4.5 mev although he does not draw his curve through them.The very broad upper level is found by him;further he suggests upon the basis of Riezler's work and his own that it is probably a P level.It would appear to be striking confirmation of the fact that the upper level is a D level,that evidence for it vanishes at 112° and evidently reappears according to Devons at 90° for this behaviour would indeed be associated with a second order Legendre polynomial which vanishes at about 120° It is difficult,however,to apply the same argument to the case of the lower P level which is not clearly in view at 137° ;exact phase reversal from the barrier scattering is always possible

It is unfortunate that there are practically no processes leading to excited states of O^{16},which might serve to confirm these findings. The only excited state,known from ${}_1H^1 + {}_9F^{17} = {}_2He^4 + {}_8O^{16}$, lies far below these,about 6 mev above the ground state Many processes which would lead to O^{16} involve the rarer isotopes

BIBLIOGRAPHY

Bethe,Rev.Mod.Phys.,9,174,1937.

Bieler,Proc.Roy.Soc.,105,434,1924.

Bohr,Nature,137,344,1937

Breit and Wigner,Phys.Rev.,49,519,1937.

Brubaker,Phys.Rev.,54,1011,1938.

Chadwick,Proc.Roy.Soc.,128,114,1930.

Chadwick and Bieler,Phil.Mag ,42,923,1921,

Darwin,Phil.Mag.,27,499,1914.

Devons,Proc.Roy.Soc.,172,127,1939.

Duncanson and Miller,Proc.Roy.Soc.,146,396,1934.

Dunning,Rev.Sci.Inst.,5,387,1934

Geiger,Proc.Man.Lit.Phil.Soc.,55,20,1911.

Geiger,Marsden,Proc.Roy.Soc.,82,495,1909.

Geiger,Marsden,Phil. Mag.,25,604,1913

Gingrich,Rev.Sci.Inst.,7,207,1936.

Holloway,Livingston,Phys.Rev.,54,18,1938

Mano,Ann.de Phys.,1,407,1934.

Mohr and Pringle,Proc.Roy.Soc.,160,190,1937.

Mott and Massey,The Theory of Atomic Collisions,1933.

Pollard,Margenau,Phys.Rev.,47,833,1935.

Riezler.Proc.Roy.Soc.,134,154,1932.

Riezler,Ann.der Phys.,23,198,1935

Rogers,Phys.Rev.,55,588,1939.

Rosenblum,Ann de Phys ,10,408,1928.

Rutherford,Phil.Mag.,37,537,1919.

Rutherford and Chadwick,Phil.Mag.,50,889,1925.

Rutherford and Chadwick,Phil.Mag.4,605,1927.

Rutherford and Kempton,Proc.Roy.Soc ,143,724,1934.

Shire,Journ.Sci.Inst.,11,379.

Wentzel,Zeits.f.Phys.,90,754.

Wright,Proc.Roy.Soc,137,677

FIG.1. General view of the apparatus.

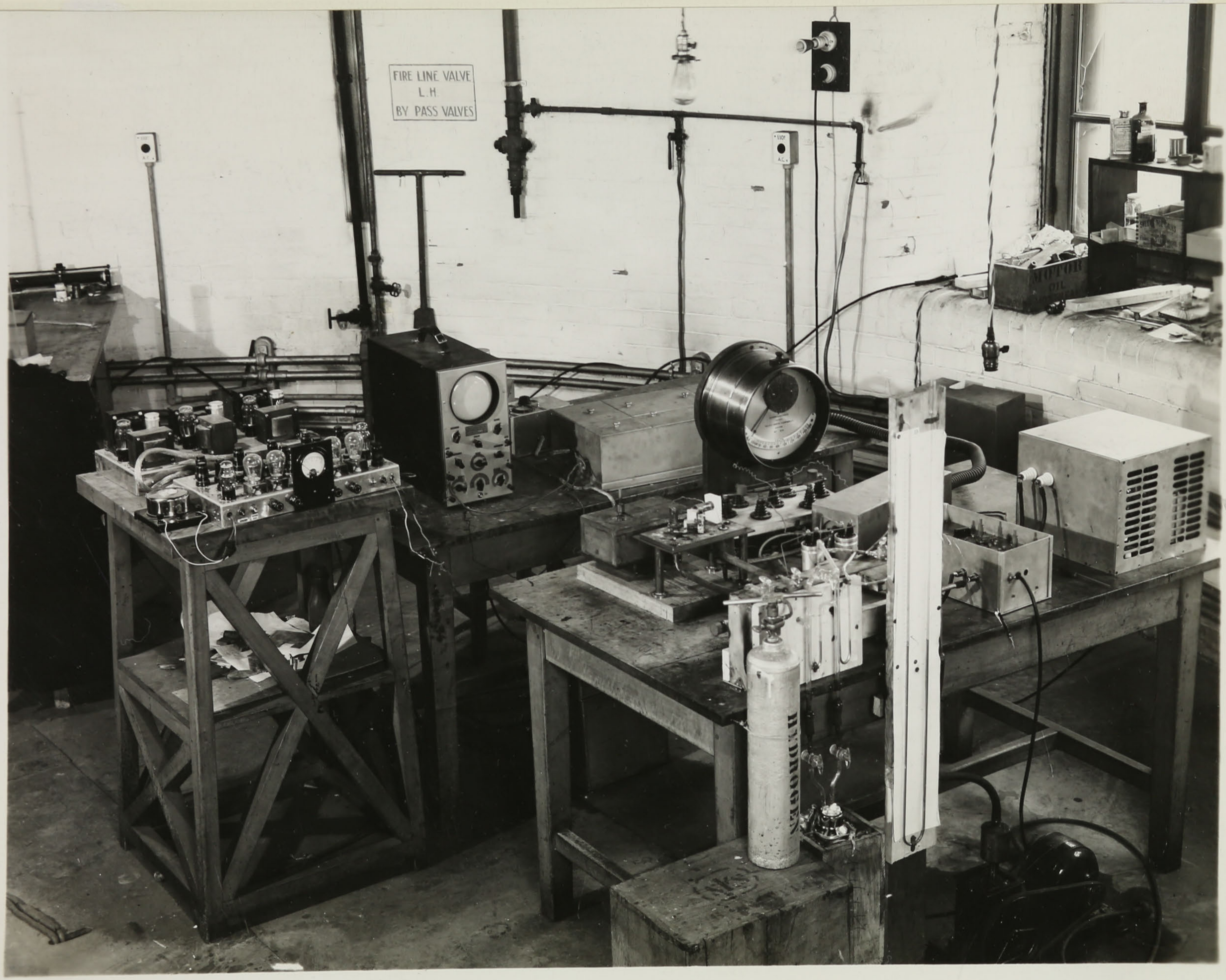
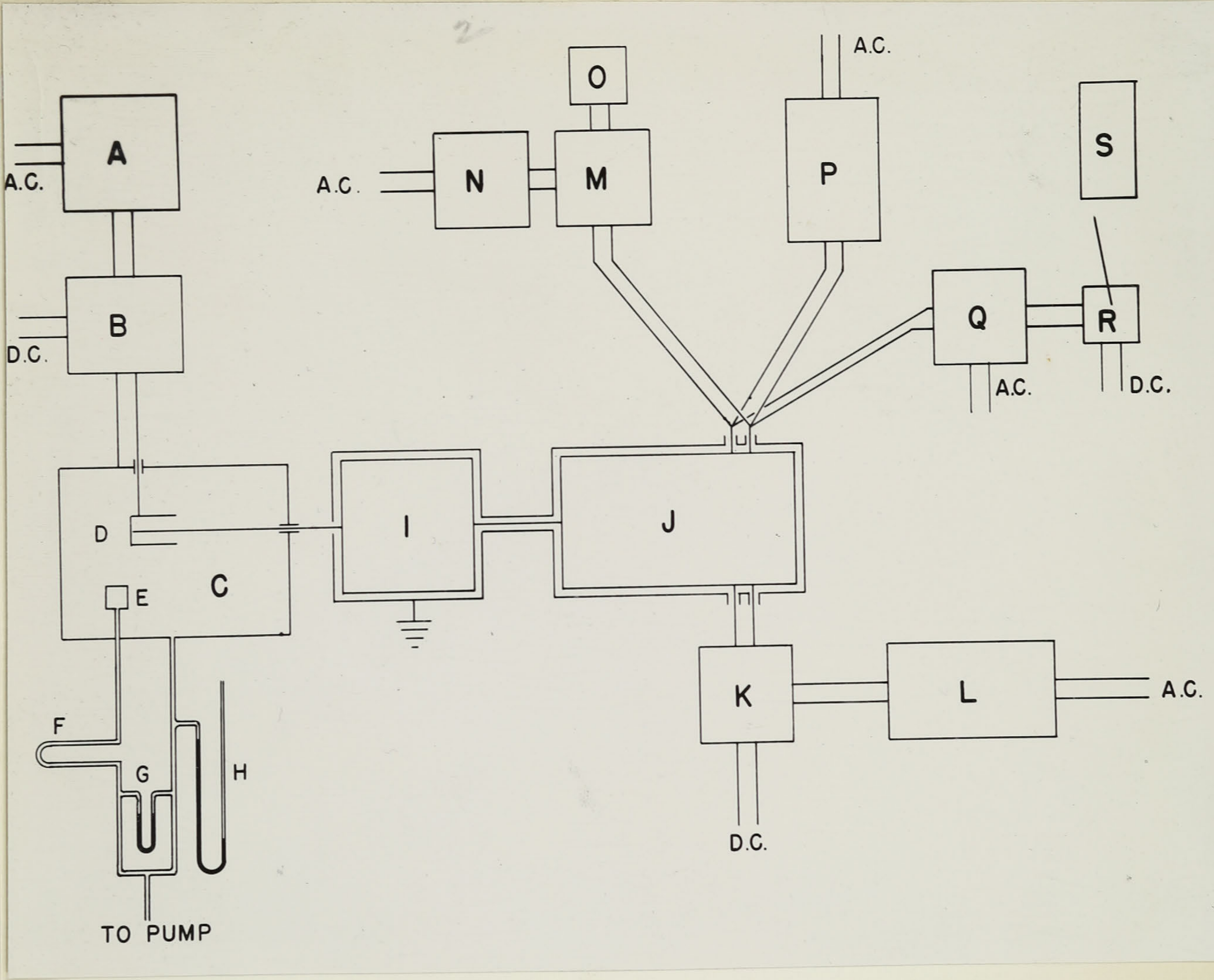
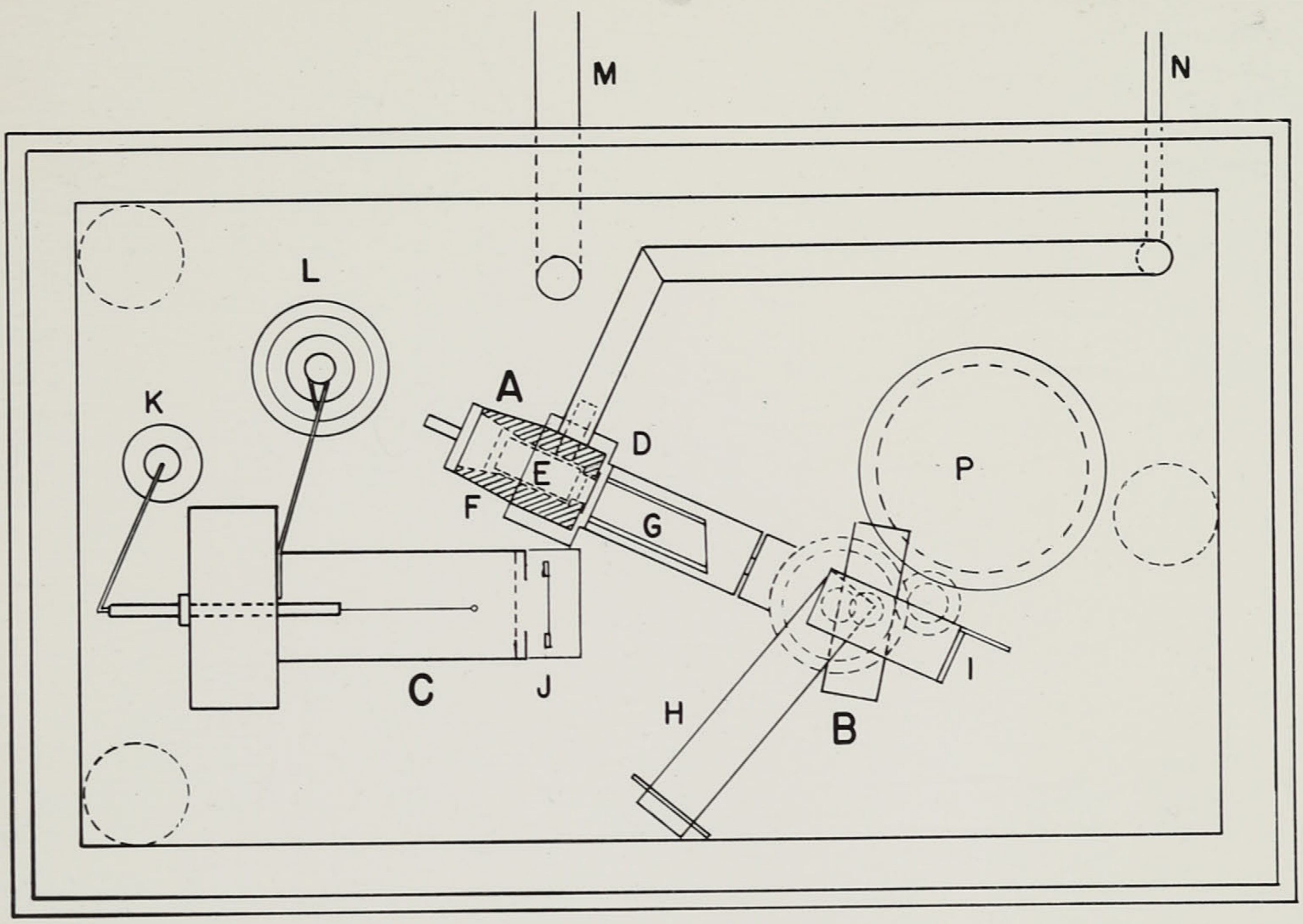

FIRE LINE VALVE
L.H.
BY PASS VALVES
HYDROGEN
MOTOR
OIL

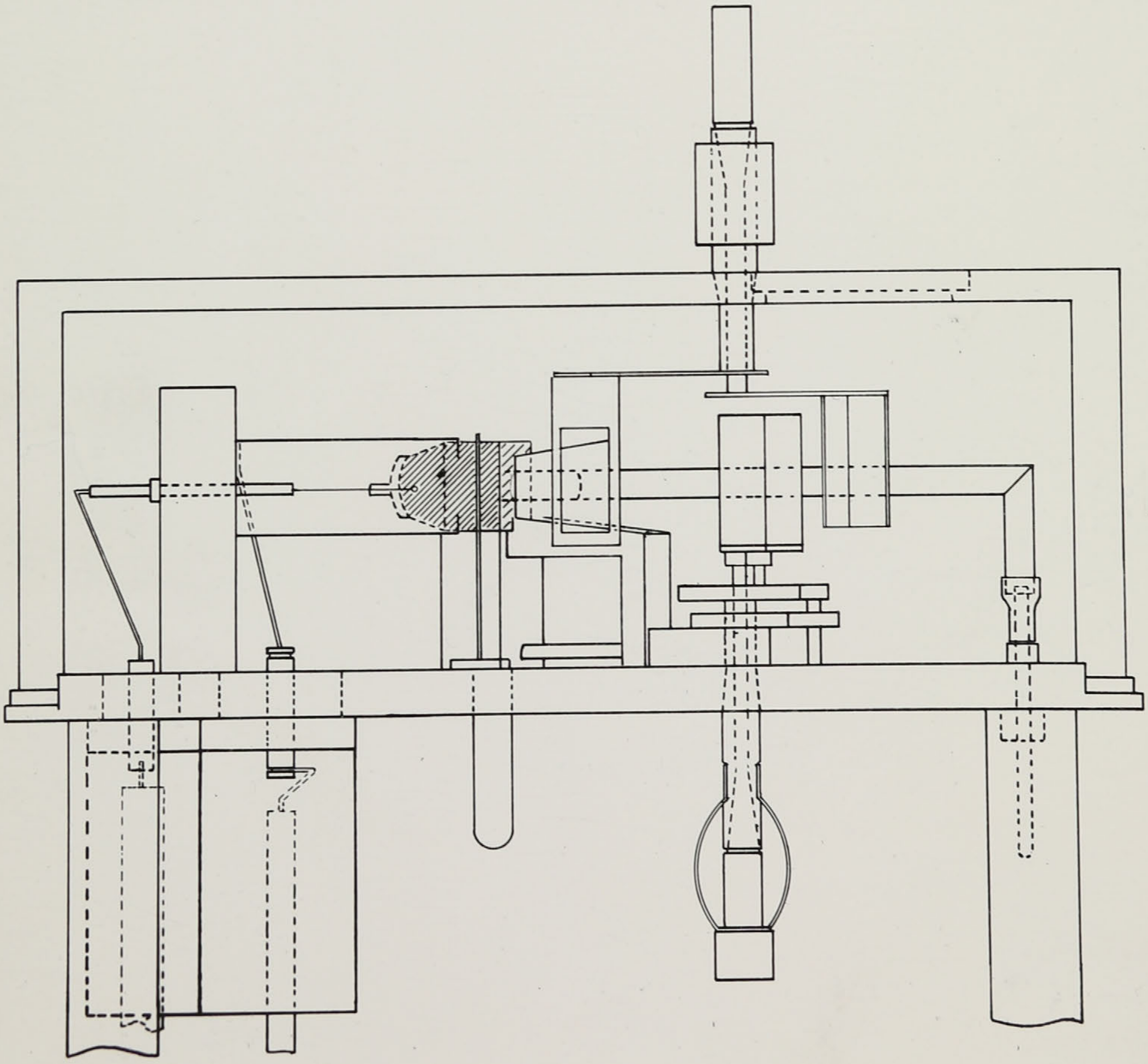
FIG. 2. Schematic diagram showing the general arrangement of the apparatus.



A. High voltage supply
B. Voltage control
C. Scattering box
D. Counter
E. Source holder
F. Charcoal trap
G. Cross manometer
H. Manometer
I. Amplifier(1st. stage)
J. Amplifier(other stages)
K. Switch box
L. Power outfit
M. Scale of sixteen
N. Power outfit
O. Cenco counter
P Cathode ray oscillograph
Q. Amplifier
R. Shire oscillograph
S. Camera

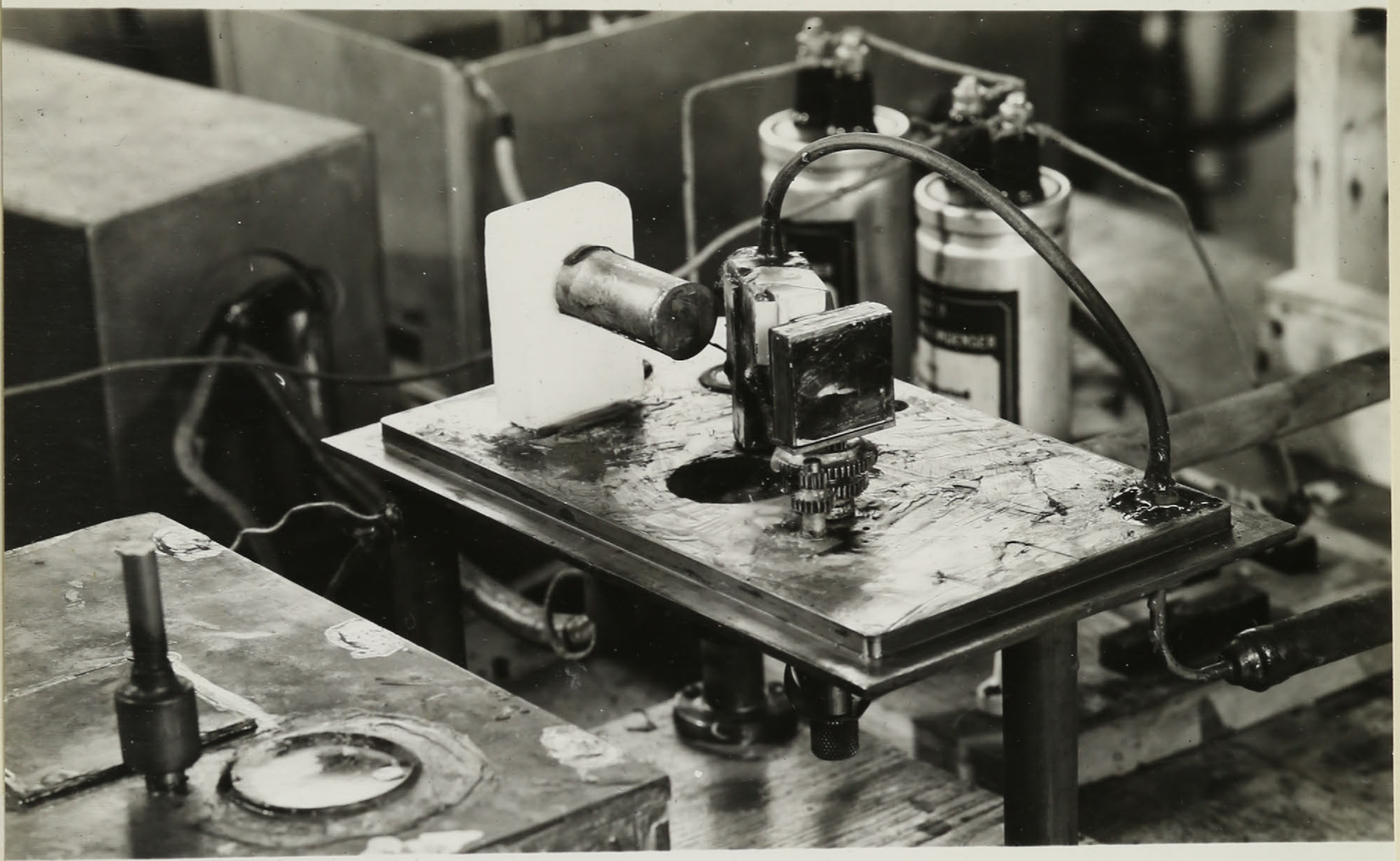
FIG.3. Diagram of the scattering box,


M
N
L
K
A
D
E
F
G
P
C
J
H
B
I



FIGS.4 and 5 Views of the scattering box.

4



5

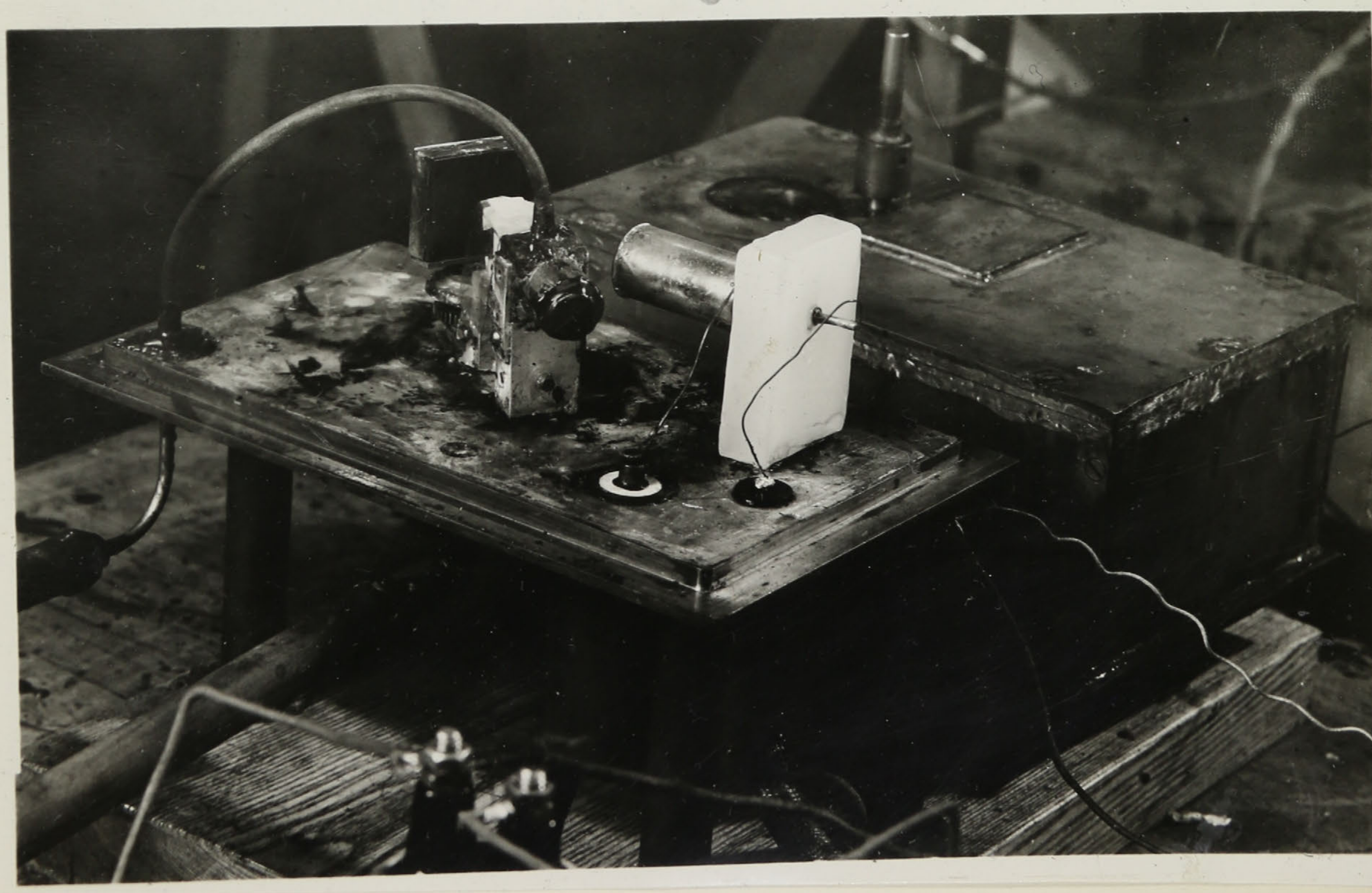


FIG.6. The scattering box closed with the old magnet in place.

6

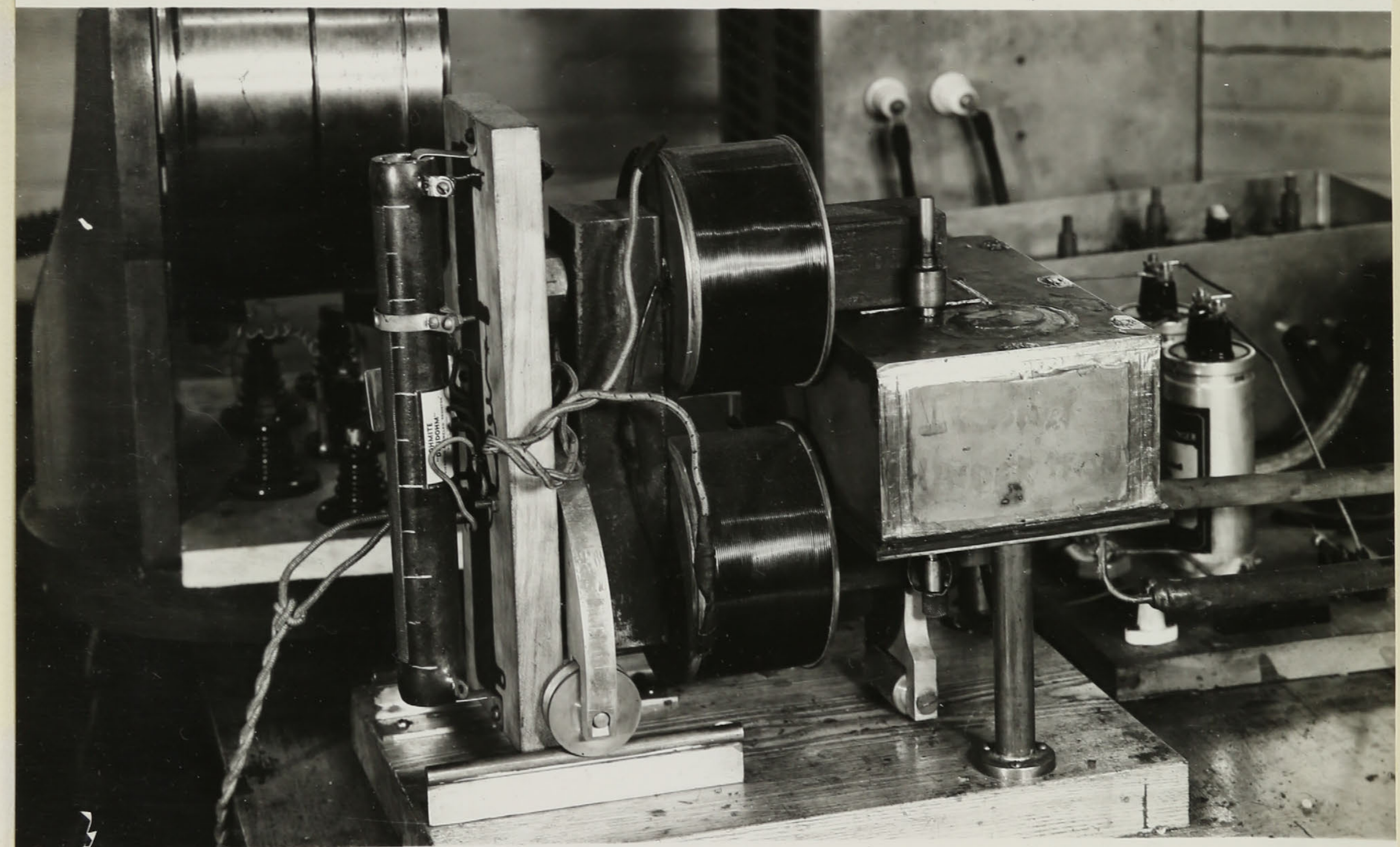
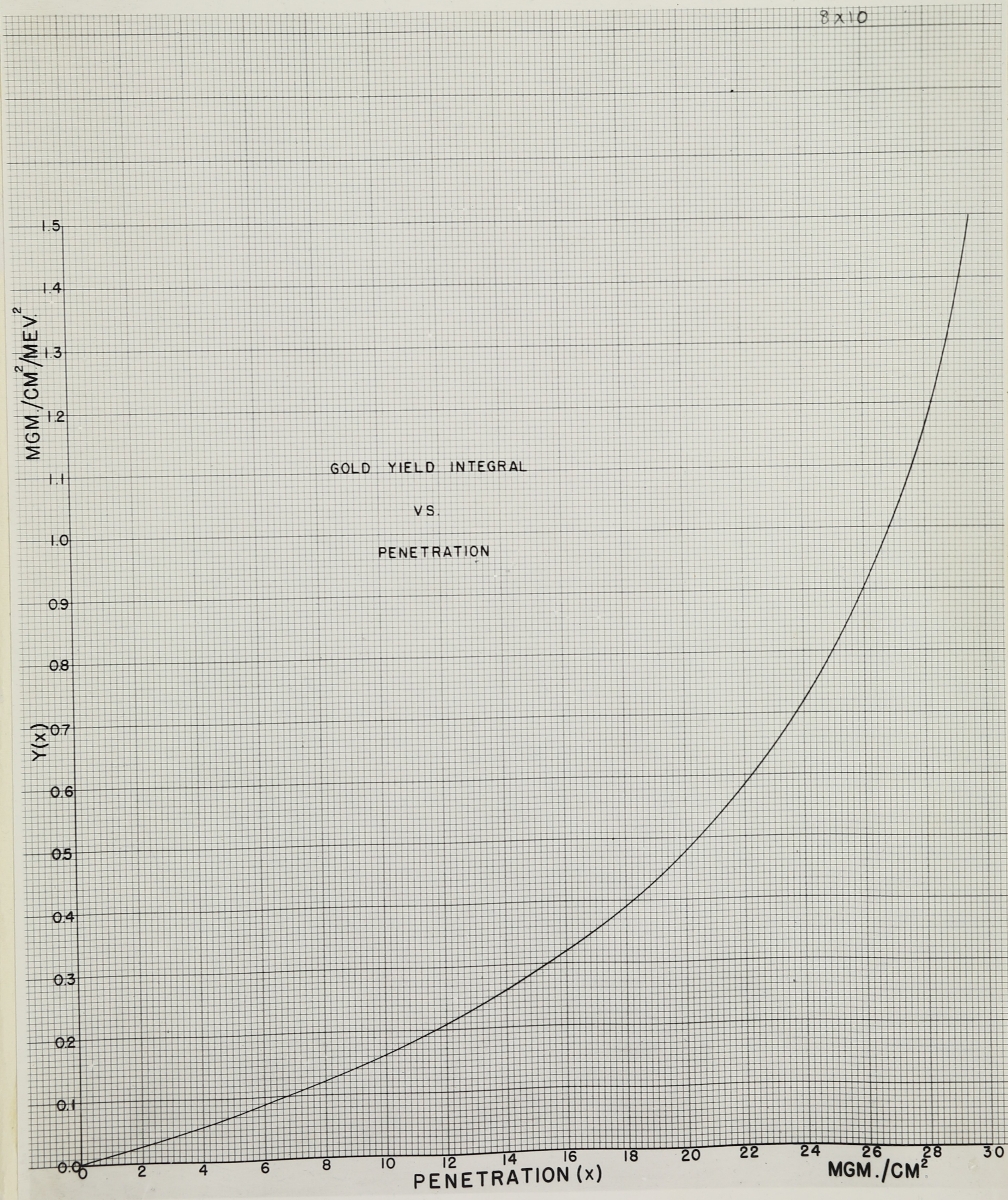


FIG.7. Graph of the quantity $I(x)$, here called $y(x)$, which determines the gold yield.

7

8 x 10



GOLD YIELD INTEGRAL
VS.
PENETRATION
Y(x)
MGM./CM²/MEV.²
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
PENETRATION (x)
MGM./CM²

FIG.8 The radium plant and source making apparatus.

6