A

THESIS

ENTITLED

A DETERMINATION BY THE CLOUD EXPANSION METHOD OF THE DIRECTION OF EMISSION OF B-RAYS PRODUCED BY X-RAYS

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Presented

by

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A B S T R A C T

Cloud expansion photographs of the photo-electrons produced in hydrogen, air, and argon by means of the $K\alpha$ radiation of Mo show that the most probable direction of emission is the same for all three gases, and forms an angle of about 70° with the x-ray beam. These angles have been measured by means of a stereoscopic comparator specially built for the purpose. The total number of tracks measured is 443. Distribution curves plotted with number of tracks starting at a given angle with the x-ray beam against the angle show a narrower peak for hydrogen than for the argon. This qualitatively supports the view that the distribution is due to secondary scattering by the electrons in the atoms thru which the photo-electron passes and that the initial direction of emission may be constant for a definite wave length and depend only on the radiation.

The study of the exchange of energy between radiation and matter has become, without doubt, the major problem of contemporary physical science. In the review of the problem one soon finds that the methods of experimental attack are readily classified into two groups; first, the type which allow a study of integral effects; and, second, the type which allow a study of individual effects. As illustrative of the first group might be mentioned ionization measurements, the blackening of photographic plates, and countless spectroscopic means. In the second group there are in existence so far, only two general methods, the Geiger counter and the Wilson cloud expansion chamber. Both of these types of apparatus allow one to work with the effect produced when a single quantum of energy falls upon matter.

The credit for the cloud expansion method is due to C.T.R.Wilson who originally developed it in 1912. Since then he, and various other workers, (see bibliography) have so perfected the method that it has now become a well known and powerful tool in modern physics.

The present thesis is the presentation of data obtained from the study of stereoscopic cloud expansion photographs of the paths of B-rays produced in various gases by homogeneous x-radiation.

Numerous workers have observed an asymmetry in the photoelectric current arising from a radiator placed in the path of ultra-violet light, x-rays, or gamma rays. The ratio of the current in the forward direction to that in the backward direction has been found to vary from 1.17

in the case of ultra violet light [1] using platinium films as radiators, to 20 for carbon plates and gamma rays. [2] De Foe[3] has recently obtained a ratio of 2.89 for the asymmetry of photoelectron paths in air, photographed by the cloud method, using the K_a radiation of molybdenum. More specifically, the most probable direction of emission of photoelectrons in gases, by means of x-radiation has been investigated by Bothe [4] and the author[5]. Using a method involving the counting of electrons by a Geiger counter set at various angles with respect to the x-ray beam, Bothe found a slight variation with the hardness of the radiation and also with gas used. His values vary from 73° to 81° for the most probable direction of emission, depending upon the above factors and also upon the gas pressure. The present author found, by photographing the tracks in air, and measuring their directions by means of a stereo-comparator (to be described in this paper) that, with K_a radiations from a Mo-target Coolidge tube, the most probable angle of ejection was about 70°.

Since the chamber used in these investigations is considerably larger than any hitherto reported and contains many new features not incorporated in its predecessors, and since further, the technic of obtaining good sharp photographs at every expansion is quite critical, it is felt that a fairly complete description of the process will be of value.

1) Stuhlmann, Phil. Mag. XXLI, p 854, 1911.
2) Mackensie, Phil. Mag. XIV, p 176, 1907.
3) De Foe, Phil. Mag. XLIX, p 817, 1925.
4) Bothe, ZS. f. Phys. 26, p 59, 1924.
5) Loughridge, Phys. Rev. 26, p. 697, 1925.

THE EXPANSION CHAMBER.

The expansion chamber is shown diagrammatically in Fig. 1, in which its dimensions have been carefully drawn to scale.

The entire apparatus is of brass except the roof 1 and the wall 2 of the expansion chamber itself, which are of glass. The roof is a disc of 3/8" plate glass, the wall a cylinder of glass 1 5/8" high cut from a $10\frac{1}{2}$" inside diameter bell jar. The chamber therefore has an inner diameter of $10\frac{1}{2}$" and so is much larger than any heretofore described. The plate glass roof is cemented to the upper face of a brass ring 5 with sealing wax, while the glass cylinder, the edges of which are carefully ground, is fitted into a groove in the lower face of this ring, and also cemented with sealing wax. This operation is best carried out in an electric oven, in which the parts are heated slowly to about 125°C and are then allowed to cool. The brass ring performs the double function of strengthening the joint between the roof and the wall of the chamber and forming the electrode by means of which the electric field is applied to the chamber. The whole is then set on top of the expansion cylinder 4 and sealed airtight below by means of soft wax, (equal parts beeswax and rosin) which is applied with a small warmed pipette, the lip of the expansion cylinder being subsequently warmed with a small blow torch to **assure** good contact everywhere. The glass chamber is held down by means of a second brass ring 3, which is secured to

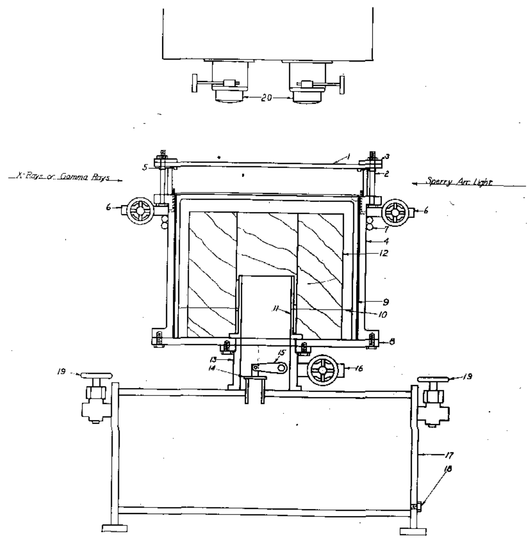


Fig. I.

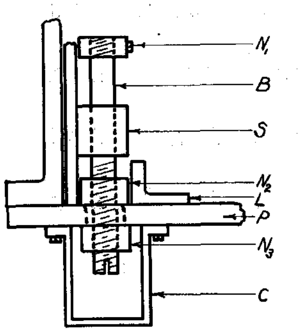


Fig. II.

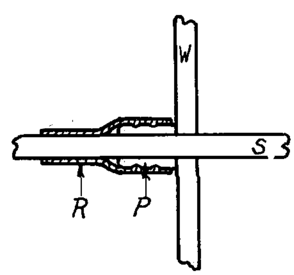


Fig III.

the expansion cylinder by means of a number of bolts. This enables the chamber to be put under pressure greater than atmospheric. Aside from the advantage in allowing gases under pressure to be studied, this is also extremely convenient in taking apart the chamber, since it is only necessary to apply compressed air through one of the needle valves 6 to lift the chamber and attached cylinder. A gasket is of course inserted between the second brass ring and the plate glass top to avoid strains. The expansion cylinder top also has a small ridge (not shown in the drawing) on the inner side to keep the soft wax from running over into the cylinder.

The expansion cylinder 4 itself (machined from a casting) is provided with a cooling pipe 7 through which tap water is run to keep water from condensing on the glass parts of the chamber, and also with two needle valves 6 for the admission of gases, adjustment of volume of gas in the chamber, washing the chamber with gas, etc. It is secured to the base plate 8 of the instrument by means of brass screws, a double gasket, consisting of a layer 1/8" sheet rubber plus a layer of 1/16" rubber dam being inserted. In taking apart the chamber these screws are loosened and the expansion cylinder with the expansion chamber attached forced up with compressed air.

The piston 9 itself (also machined from a casting) is provided with a ridge around the edge of its top face to hold in the gelatin coat. In our case the piston itself weighs some thirty pounds, the whole being made massive for various reasons: to retain its shape; to act without vibration, to enable piston rings to be inserted, and reduce possibility of leaks (porosity of casting). This relatively large weight introduced a new difficulty, namely that the water level 10 in the cylinder was too high, a condition which resulted in splashing and even in water flowing over the top of the piston. However this whole difficulty was easily remedied by supporting the weight of the piston by means of a phosphor-bronze compression spring (not shown in the drawing) seated on the top of the central valve cylinder extension 11.

The space underneath the piston is filled up as completely as possible by means of a wooden ring 12, which is carefully treated with paraffin to make it watertight.

The vertical wall of the piston (Fig. 2) has soldered to it a sleeve S, which slides on a vertical bolt B. The latter carries at its upper end a nut N_1 (provided with a set screw) which limits the height of rise of the piston. The bolt at the same time keeps the piston from rotating. In order that the height of rise of the piston be adjustable from the outside, this bolt is threaded below through a square nut N_2, which is kept from turning by an L shaped stop L soldered to the base plate P. The bolt can be raised or lowered by means of a screw driver. To make the seal tight the bolt is further provided with a nut N_3 with a collar, over which is slipped a piece of tight fitting rubber tubing, which in turn fits into the aperture in the base plate of the apparatus. As an additional precaution against leaks, a brass cylinder C with a rubber gasket is fastened over the projecting part of the bolt.

The base plate is provided with two apertures which serve to admit the two tubes of a water gauge. One of these tubes ends flush with the floor of the chamber; the other extends vertically beyond the water level. On the outside of the chamber these two tubes terminate in nipples to which two pieces of rubber vacuum tubing can be attached. The latter connect with the two ends of a vertical glass, in which the water level can be observed. To fill the chamber water is poured into the upper tube, which is slipped off the gauge and attached to a funnel for this purpose.

The water level itself need be only an inch or so above the floor of the cylinder. Too high a level may cause the water to splash during an expansion and must be avoided. The counterbalancing of the piston serves to keep the water level down. It the piston is not counter-balanced, the water level between the piston and cylinder wall may rise until it is near (or even above) the top of the piston. In this case splashing is hard to avoid.

Another cause of splashing, particularly if a stop is used to limit the height of rise of the piston, is a leak of air out of the upper chamber either around the piston gasket or through the piston itself. If the air is gradually sucked out of the chamber, the air in the latter will of course be at reduced pressure. Ordinarily, with no stop, the piston would rise higher on being let up until equilibrium is again restored. However with the stop this cannot take place and the water rises instead.

For this reason the leak of air out of the chanber must be avoided. This is done by choice of proper gasket on the one hand, and the avoiding of porosity in the piston on the other. The second point is taken care of covering the inside of the piston with soft wax.

The base plate 8 has a circular aperture which opens into the valve cylinder 13. Projecting upward from this aperture is the valve cylinder extension 11--a cylinder about 3½" high, which prevents water from entering the valve cylinder. The valve cylinder itself contains the expansion valve, which on being opened produces the expansion.

The consistent action of this valve is important, since it affects the timing. Leaks also must be avoided since they cause the piston to creep. In order to insure that the valve seats properly, two small phosphor-bronze fingers (not shown in the figure) are introduced which act as guides and keep the valve cap from tilting. The under side of the valve cap has a rubber gasket which is attached rigidly to it by means of a brass disc held by a screw.

The valve cap 14 is carried by one end of a lever 15, the other end of which is mounted on a shaft, which runs through the wall of the valve cylinder and is manipulated by means of an electromagnet from the outside.

The manner of making an airtight seal between the shaft and wall of the cylinder is shown in Fig. 3 where S represents the shaft, W the wall of the cylinder, P a cylindrical projection, and R a piece of rubber tubing the two ends of which are sealed with shellac. This manner of making the seal is possible because the shaft need rotate only through a small angle. The outer end of the shaft carries a double lever arm, one end of which is attached to the plunger of an electromagnet, while the other is fastened to a spring which presses down the valve cap against the valve opening, and so assures a good seal.

The valve can be opened slightly by pressing down one end of the outer lever. This is convenient for producing slow expansions in clearing out the chamber and also in setting the piston. The piston is let up by admitting air through the needle valve 16, and let down by pressing lightly on the outside lever arm. If the piston is let down slowly by pressing lightly on the lever arm, the formation of a general cloud can be avoided.

The manipulation of the piston is then, after an expansion to let it all the way up by opening needle valve 16, to reduce the tendency of the air to leak around the piston gasket, and allow it to remain in this position until the time comes for another expansion. Then, by pressing slightly on the lever arm after closing valve 16 the piston is allowed to fall slowly until it is somewhat below the correct setting, and now it is allowed to rise to the proper setting by opening the needle valve. With a little practice the whole

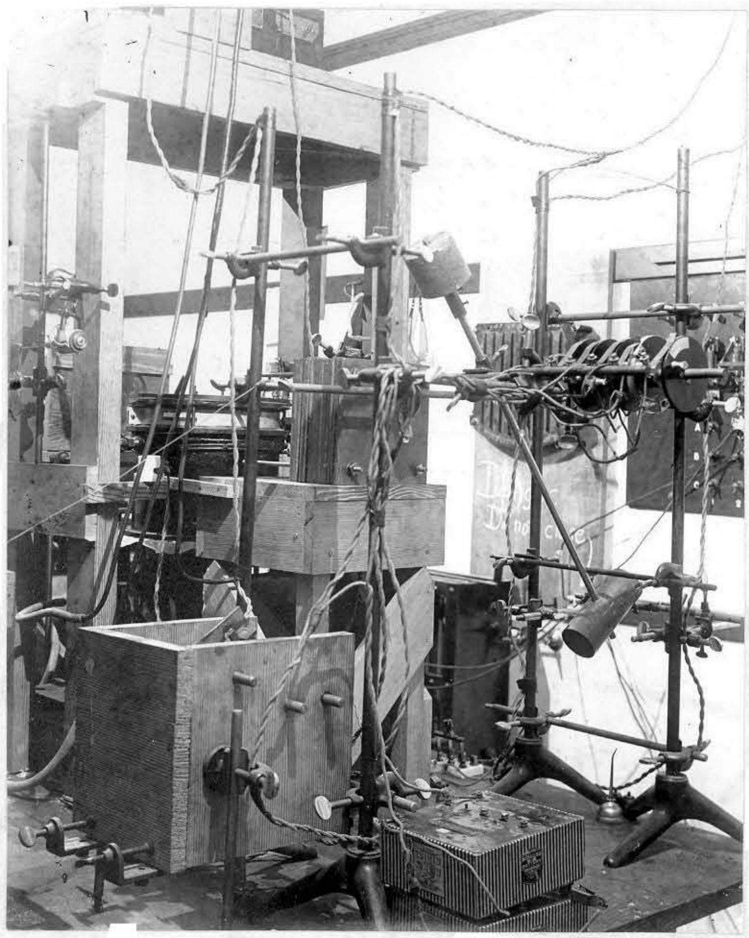


Fig IV

operation can be carried out very rapidly.

Accessibility is an important requirement of the valve, since it may occasionally need a new gasket or some adjustment. For repairing the valve the expansion chamber plus the expansion cylinder is lifted off entirely, and also the valve cylinder extension.

The lower vacuum chamber 17 is provided with a drain plug 18 and also two valves 19, one of which leads to a mercury manometer and the other to an aspirator pump. As such was used four large brass filter pumps connected in parallel.

THE PENDULUM

The timing pendulum (Fig. 4) consists of the bob mounted on the lower end of a rod, the upper end of which is attached to a horizontal shaft. This shaft, which is mounted in well oiled bearings to eliminate friction, carries four commutators, each of which is simply a fiber disc with a metal inset on its periphery. Four stationary metal phosphor-bronze brushes slide one on each of the peripheries of these discs and establish the contact with the metallic segments. Three of the commutators have a single segment each, the fourth (that controlling the electric field) has a double segment so arranged that when the pendulum is drawn back the voltage is applied to the ring electrode of the expansion chamber but so that just before the rays enter the voltage is cut off and the ring electrode grounded.

Each of the fiber discs is fixed to a short brass cylinder, (collar) which slips over the shaft of the pendulum, and can be rotated with reference to the shaft so as to vary the point at which the contact takes place between the metallic sector and stationary tongue. The brass collar is of course provided with a set screw. It is also very convenient to provide the fiber disc with a circular scale and the pendulum shaft with a pointer (index) which plays over this scale, so that the angle through which the disc has been displaced with reference to some arbitrary zero line on the shaft can be read off. This is extremely convenient for adjusting the timing.

The pendulum is released by means of a spring catch, which can always be set at the same point and does not impart any momentum to the pendulum. The pendulum is caught at the end of its swing by a second catch, which is arranged to trip a master switch, which then cuts off the current through the electromagnets, and the primary current of the x-ray transformer.

When the primary current is first impressed on the x-ray transformer the transient voltages are such that homogeneous radiation could not be relied upon by simply using flashes of the primary current so that the tube was started running by hand, before the timing pendulum was released. This avoided the presence of the transient voltages when the expansion occurred. The admission of the beam of x-rays at the correct time was controlled by a small lead slit which moved in front of the collimating tube of the x-ray box.

This slit was in turn controlled by an electromagnet energized by a commutator on the pendulum axis.

When gamma rays are used, a second auxiliary pendulum is used. The radium is attached to the bob of this auxiliary pendulum, which is actuated by the shaft of the main pendulum through a rod (of small diameter) which forms a prolongation of the shaft of the main pendulum. The whole arrangement is enclosed by means of a lead block, 8" on a side, built up of sheets of 1/4" lead bolted together.

TECHNIQUE

A discussion of the technique of the Wilson cloud expansion chamber centers around four important points: (1) The production of an accurate expansion ratio (2) An accurate timing of the events (3) A clean chamber (4) Elimination of disturbing air currents.

1. The Expansion Ratio. An accurate duplication of the expansion ratio is absolutely essential if consistent results are to be obtained. The exact ratio varies a little with temperature, speed of descent of the piston, nature and age of the gas in the chamber, etc., so that it is best determined by a few trials before each run.

It has been found that the expansion ratio must be adjusted with great accuracy, a variation of one tenth of a millimeter (where the total drop of the piston is 9 mm) in the setting of the piston producing a considerable variation in the clearness and sharpness of the tracks. Since the absolute ratio is not of great interest, it is convenient merely to duplicate accurately the setting of the piston. This can be done by means of a short focus telescope with a micrometer scale in the eyepiece, the telescope being rigidly attached to the chamber. The telescope is focused on some convenient scratch on the piston, and the correct setting found by a few trials. For absolute determinations a cathetometer is employed.

For an accurate adjustment of the height of the piston, the pressure below it is regulated by admitting air through a needle valve. The latter must be capable of very fine adjustment and must also seal perfectly, since a very small leak would enable the piston to "creep" past the correct setting. Ordinary brass needle valves are entirely satisfactory for ease and rapidity of adjustment, and also for air tightness.

In order that the ratio, once accurately determined, shall stay constant to a high degree of accuracy, other factors must also be maintained constant. In the first place the speed of descent of the piston must be kept fairly constant. This is effected by adjusting the pressure in the vacuum chamber approximately to the same value, a mercury manometer being attached to it for this purpose. In addition the expansion valve mechanism must function consistently. Aside from the proper design of the valve, this means that in our case, where an electromagnet is used, the current through the latter also must be kept fairly constant.

It is evident that any form of leak will interfere with the accurate setting of the piston and therefore the consistent operation of the chamber. In fact leaks account for most of the troubles encountered in the operation of the chamber so that it is worthwhile to consider them in detail.

Leaks may be classified as follows: those between the chamber and the air outside; those between the chamber and the space below the piston; and those between the space below the piston and the air outside.

Unless the gas in the chamber is at a pressure greater than atmospheric, the first kind of leak mentioned above takes place only from the air outside into the chamber. Such a leak is detrimental for two reasons: first, it changes the mass of gas in the chamber and, second, it changes the nature of the gas in the chamber. The latter point has to do with the cleanliness of the gas and will be discussed separately under that head. The existence of the leak in question is easily detected by the fact that the equilibrium height of the piston i.e. the height to which it rises when the space below it is opened to the air, continually decreases.

A leak from the space under the piston into the chamber may take place either through the piston or around the piston gasket. The existence of such a leak is manifested by the equilibrium height continually increasing. To avoid a leak through the piston the latter is coated on the inside with a layer of soft wax, or other material not attacked by water. If the seal between the piston and piston gasket is imperfect, then the pressure of the air in the chamber drives the water (on which we rely for the air seal) around the gasket into the space under the piston and finally some of the air leaks directly into the space beneath the piston.

Since, however, this process requires appreciable time it can usually be forstalled by letting the piston up again immediately after an expansion, and the apparatus has always been operated in this way.

For the gaskets various kinds of rubber have been tried. The gasket, in addition to making the seal, must also absorb the shock of the piston and must do this smoothly. After trying various kinds of rubber it was found that a layer, 1/8" thick, of grey sheet rubber (known commercially as staple sheet packing) plus a layer of 1/16" pure rubber dam is most effective. The first takes up the shock, and the second makes the seal.

The third kind of leak, namely that into or out of the space below the piston will only affect the height to which the piston is set. A leak into the chamber usually occurs through the needle valve and is manifested by the piston creeping upward after it has been set, until it has reached the equilibrium setting. A leak of this kind is usually easily remedied. A leak into the vacuum chamber is usually due to an imperfect seal of the gasket on the expansion valve, and is manifested by the piston creeping downward after setting. This leak also is easily remedied by proper adjustment of the expansion valve and its gasket. Unless the latter is rigidly attached to the valve cap, the rubber of the gasket may be held down on the valve opening due to the suction, for this reason it is best to attach the gasket to the cap by means of a disc or a ring, or both, so that the rubber will be drawn up with the cap. In some cases we have fastened the rubber gasket on with sealing wax and a metal disc.

The speed of descent of the piston is controlled by the size of the opening of the expansion valve, the height to which the cap is lifted, the speed of operation of the valve, ratio of volume of vacuum and piston chamber, ratio of pressures, etc. The descent should not be too violent.

Another requirement under the head of the attainment of an accurate expansion ratio is that the piston does not rotate as otherwise the scratch observed through the telescope will pass out of the field of view. In order to obviate setting the piston for each expansion by means of the needle valve and telescope, it is desirable to provide a second adjustable stop which, once set at the proper point, automatically allows the piston to rise to this point. A stop which performs both of these functions has been introduced, but so far this has not been entirely practical as far as the second one is concerned due to the fact that is difficult to manipulate and that it does not stay in close enough adjustment. We have found it much easier to set the piston each time with the needle valve and telescope. From the point of view of automatic devices, however, the perfection of such a stop is extremely desirable.

2. <u>Cleanliness of the Gas in the Chamber</u>. By a "clean" chamber we shall define one which contains, at the instant of expansion, no condensation nuclei except those it is desired to observe.

The undesirable nuclei can be divided into two classes (1) those electrical in nature (2) and those not electrical in nature.

The first class, which consists of ions left over from previous expansions or produced by stray radiation, radioactive contamination, etc., is easily removed by electrical precipitation. It is only necessary to apply a difference of potential between the roof and floor of the chamber. For this purpose an electrode in the form of a flat ring is placed on the roof of the expansion chamber and a difference of potential applied between this ring and the base of the expansion chamber. The magnitude of this potential will vary with the intensity of the stray ionization and the interval between expansions. If an alpha ray source is being examined and expansions made in rapid succession a potential difference of 200 volts may be necessary to clear out the chamber; if, on the other hand, x-rays or gamma rays are being examined, a few volts usually suffice. This field of course must be cut off just before the rays to be observed are admitted to the chamber, and this requires not only that the source of emf. be disconnected from the chamber, but that the ring electrode actually be grounded to the chamber.

When high electric fields are used and a bare plate glass roof (i.e. if no gelatin coat is used) the sharpness and clearness of the tracks is extremely sensitive to changes in electric field. Too low an electric field is not sufficient to remove the stray ions, while too large an electric field causes the tracks to become fuzzy. The explanation of the latter phenomenon is no doubt that charge creeps out on the glass roof of the chamber and is not discharged completely (due to the high resistance of the surface of the glass) before the new rays are admitted. With a clear glass top and x-rays or gamma rays as the source we found, as did C.T.R. Wilson, that a gradient of about 4 volts per cm is sufficient.

With a well conducting gelatin coat on the roof of the chamber much greater potentials can be applied without appreciable effect. The ideal condition would be to have a transparent conducting layer for the roof of the chamber, and perhaps this is an argument for retaining the gelatin layer on the roof of the chamber.

However, large fields are not vital, for most ordinary purposes the bare glass top and inserted ring electrode will suffice. The absence of the electric field is quickly manifested by the appearance of bulky "cumulus" clouds in the chamber. The correct adjustment of the electric field is absolutely essential to sharp tracks.

The second class of undesirable nuclei, namely those which are uncharged, are not so easily dealt with. No doubt a large percentage of this second kind is made up of dust particles. C.T.R. Wilson has shown that water condenses on the dust particles before it condenses on the electrical nuclei, and therefore it is desirable to remove this dust.

It is always found that when fresh air is admitted large numbers of stray ions, which manifest themselves by clouds superposed on the tracks after an expansion, are present. The correct expansion ratio also appears to be extremely critical under these conditions. This effect diminishes only with time, although certain factors seem to hasten the process. After the air has been aged, the remaining nuclei can usually be precipitated by a few slow expansions before each run. If these disturbances are due to dust any agency which will remove the dust should hasten the process of "cleaning out."

A very moist gelatin coat on the piston top is extremely effective in cleaning out the chamber, no doubt due to its property of absorbing the dust which falls on it. In one instance where the gelatin coat on the piston top had been heated until it became fluid and the chamber was then immediatly sealed up, very beautiful clear tracks were obtained within a few hours after sealing up the chamber.

When the correct expansion ratio is exceeded, that is when an overexpansion is produced, the nuclei formed seem to persist for some time, and can only be removed by a number of slow expansions. It is therefore best to avoid overexpansions, in finding the correct expansion ratio it is best to approach it from below.

3. Timing of the Events. The third essential in the operation of the chamber is the accurate timing of the events, namely: the collapse of the electric field, the

expansion, the admission of the rays, the photographic exposure.

Of these four intervals the one between completion of expansion and admission of the rays requires accurate adjustment. After the drop pattern has been formed, it persists for an appreciable time before gravitation and air currents interfere, so that the timing of the photographic exposure is not critical. The electric field should be reduced to zero just before the rays are admitted, if charges have crept out on the glass top of the chamber, the ring electrode should be grounded soon enough to permit this charge to leak off.

For the purpose of the timing we have used a single pendulum which times the various events through electrical contacts of a multiple commutator mounted on its shaft. This commutator (1) cuts off the voltage from the ring electrode and then grounds the latter to the base of the expansion chamber (2) produces the expansion by sending current through an electromagnet which opens the expansion valve (3) admits the rays and (4) makes the exposure.

The admission of the rays can be carried out in various ways depending in the nature of the source i.e. whether it is an x-ray tube or a quantity of radium.

If x-rays are used and flashes are satisfactory for the purpose in hand, then a pulse can be sent to the primary of the transformer through the commutator. If quantitative results are desired i.e. if the voltage applied is to be accurately known or if direct current is used, then it is best to keep the x-ray tube running continuously and admit the rays through a slit in a moveable lead screen controlled by the pendulum.

If gamma rays are used a moving lead screen would be rather cumbersome. However in this case the source itself can be moved past a slit in the manner already described. For this purpose the radium is mounted on the bob of a small auxiliary pendulum, which is rigidly attached to the shaft of the main pendulum and swings in sychronism with it. The auxiliary pendulum, which need be only a few inches long, is placed inside a lead block to shield the chamber from the gamma rays.

4. Vortex Motion. This last point needs only brief discussion. It is clear that any air currents (vortex motion) will distort the drop pattern produced and must be avoided. At the instant the piston moves down the air rushes from the volume above into the space vacated by the piston and if the cylinder walls are straight and flush with the piston walls, if no obstacles intervene, and if the piston moves down without any vibration, the air will be displaced parallel in the direction of motion of the piston and come to rest without any disturbance. If however, the cylinder walls are recessed, or if side tubes are provided, then the air will rush out of these spaces, and produce a violet turbulent motion, which interferes seriously with the tracks. The

chamber walls should therefore be nearly a prolongation of the cylinder walls, and all side tubes should be avoided. If a side tube is introduced it should not extend into the chamber, and, furthermore, be provided with a stopper which comes flush with the inner wall of the chamber. Obstacles inside the chamber should also be avoided, since these have a tendency to deflect the air and set up turbulent motions.

If obstacles are introduced they should have walls which are parallel to the direction of motion of the piston and extend the full height of the chamber. If care is taken, although it may not be possible to eliminate the vortex motion entirely, it can at least be so reduced that it does not reach the tracks until after they have been photographed.

ILLUMINATION AND PHOTOGRAPHY

For visual work a single 500-watt stereoptican Mazda lamp can be used to illuminate the tracks. Remarkable differences in intensity of the tracks can be noted depending on the angle at which the tracks are viewed. The tracks appear brightest when the observer looks in the direction of the source of light but at a small angle to the direction of the incident beam.

A small flash light lamp is also required to illuminate the scratch on the piston used to set on.

For photographic work a very intense source is required, particularly if the photographs are taken in a direction perpendicular to the illuminating beam. As such, a powerful arc light (Sperry arc) is used. Regular Sperry cored carbons carrying 150 amps are found to be necessary to give an intense enough light.

The arc is provided with a shutter so that the light can be admitted only at the instant it is needed. Unless this is done extraneous clouds are formed. Whether these are due to local heating or to ionization or to both, has not been investigated.

It is desirable also to keep the light off of the bottom of the chamber. This can done by rendering it parallel with a cylindrical lens, and also by admitting it through parallel slits (rectangular apertures.).

With this type of illumination very fast plates are necessary. For this purpose Eastman "Speedway" plates have been found satisfactory, although their grain is quite coarse. I have used specially matched Tessar lenses (20 Fig. 1), using their full aperture f 4.5. These provided sufficient depth of focus to cover the whole chamber depth. An 8 x 10 Graphlex focal plane shuttersimultaneously exposed two plates.

MANIPULATION AND ADJUSTMENT.

An important detail in the manipulation of the chamber is the preparation of the gelatin coats. The function of the opaque coat on the floor of the chamber is to catch the dust, provide a black background, and presumably also to hold some moisture. I have used the following mixture;

50 cc of hot water, 5 grams of gelatin, 5 cc of a 5% solution of phenol in alcohol, 0.5 grams of lampblack, 0.2 grams of copper sulphate or boric acid. The mixture is poured on while still warm enough to be fluid. It is poured through cheesecloth, which removes lumps, bubbles, etc. In fact the use of the cheesecloth assures an absolutely smooth, clean, and glassy coat. The piston top should be warmed beforehand.

The transparent coat for the roof of the chamber is prepared by dissolving 5 grams of gelatin in 100 cc of hot water and adding 5 cc of a 5% solution of phenol. This mixture is also poured through cheesecloth, the chamber (turned bottom side up) being previously carefully leveled with a spirit level. It is extremely important to have the surface on which the gelatin is poured dry, to assure good contact everywhere. The coat is made only a few millimeters thick, and allowed to dry over calcium chloride, a small lamp being used to promote circulation of the air.

The apparatus being assembled with the gelatin coats in place, water is poured in through one of the tubes leading to the glass gauge, and then the apparatus is ready for adjustment.

Unless measurements are to be carried out at reduced or increased pressure, the mass of gas in the chamber is adjusted so that on an expansion the ratio of volumes will be somewhat in excess of 1.3. This is done by opening one of the needle valves and forcing up the piston until it is at the proper height, and then closing the valve. (It may now be necessary to wait for a few hours until the chamber has become clean enough to carry out the next step.)

Next a few slow expansions are made to precipitate the dust. If this test shows that the chamber is fairly clean, the final adjustment can be made. This consists in finding the correct setting of the piston and of the commutator which controls the expansion. For this purpose it is best to use a fairly strong beam of x-rays of gamma rays.

Beginning with settings below that required to give a ratio of volumes of 1.3 and with the commutator set so that the rays enter after the expansion, the piston is gradually set higher and higher until the setting is found at which fuzzy tracks begin to appear. This setting is just short of that which produces a general cloud. If a general cloud has been produced, a number of slow expansions are made to precipitate the nuclei formed. When fuzzy tracks begin to appear, (it may be necessary to vary the commutator setting somewhat) then the fine adjustment is made. This consists in varying both the piston setting and the expansion commutator setting until the best combination is found for sharp tracks. As a final adjustment it may be necessary to vary the field somewhat, especially if no gelatin is used on the roof of the chamber. It is also necessary finally to decrease the intensity of the x-ray or gamma ray beam until that giving the desired number of tracks is attained.

If extraneous clouds continue to appear, either the air in the chamber has not aged sufficiently or the field is not working. The presence or absence of the electric field and also changes in its value, produce great differences in the clearness and sharpness of the tracks.

In the foregoing it is of course assumed that no leaks occur. Leaks produce erratic performance of the chamber. The detection and remedy for the leaks have already been discussed above. After the tracks have been obtained visually, the timing of the photographic apparatus is adjusted, and the apparatus is ready for use.

MEASUREMENT OF THE PLATES.

Measurement of the plates was carried out on the original negatives. The stereocomparator is shown is fig. 4. It was machined from brass castings and consists of a heavy bed plate upon which the first carriage slides; the latter in turn carries the second carriage, and the two are moved relative to one another by the micrometer screw. Each carriage supports a cross hair which is stretched across, horizontally, at such a height as to just clear the plates, which lie in a suitable support on the bed plate. It was found practicable to have the cross hair clear the plates by about 0.5 mm. although this would flucuate some due to the differences in the thickness of the plates. The advantage in having the cross hairs as close to the plates as possible was to eliminate parallax.

The arrangement of the apparatus is such that the direction of the x-ray beam is in the vertical plane con-

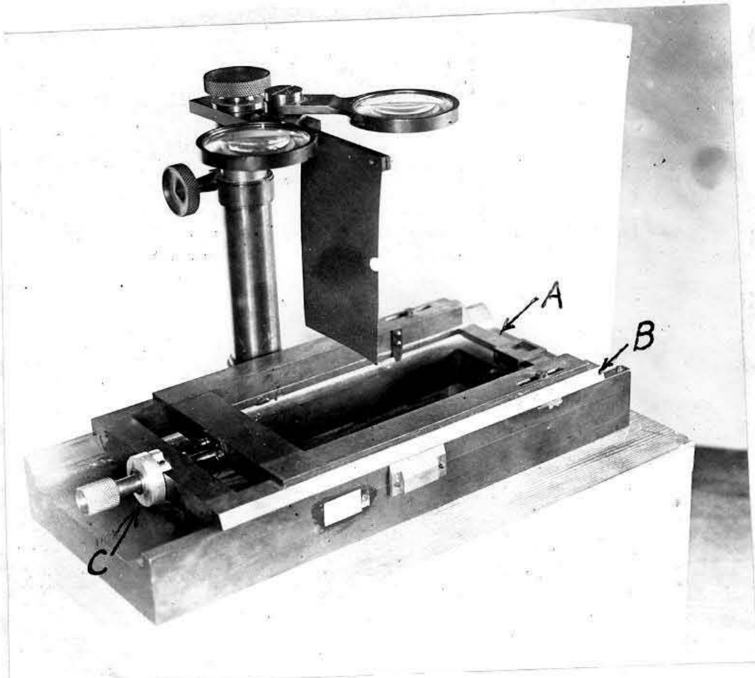


Fig IV.

taining the centers of the two camera lenses. Consequently components of tracks at right angles to this plane will be of the same length in each plate of the pair; this dimension is measured by the slider A which runs over a cross bar graduated in mm., with vernier reading to 0.1 mm., and this measurement, called the height, is made upon the right hand plate. Components parallel to the incident beam, called the width compoments, are measured by the scale B which is engraved upon the bottom carriage and is provided with a vernier on the bed plate reading to 0.1 mm. Components perpendicular to the plane of the photographic plate, called depth components, are measured by the drum C, mounted on the micrometer screw. Turning of this screw alters the distance between the two cross hairs but, in stereoscopic relief, appears to move the single cross hair, seen in the image space, perpendicular to the plane of the plates.

In the actual measurement of a track, the plates were placed in the bed plate, touching each other, and scale B read when the left hand cross hair was just over the junction point of the two plates. This was to allow the plates to be put back at any future time and the measurements on any particular part of the plate repeated at will. Thus no marking or scratching of the plates was required to reset them at their original positions. The arc light, used for the illumination, produced a caustic by reflection from the opposite side of the chamber from which it entered and this automatically insured the placing of the right side up.

Only those tracks which were entirely separate from all others throughout their entire length, and in which there was no doubt as to what was their head (or origin) were used in the measurements.

In a number of cases two photoelectron tracks started at the same point, as near as could be told, and if they were otherwise free from other tracks, both were used for measurement. There are two general means of distinguishing the origin from the end of a track, and usually they could both be used on a given track. The first, and more obvious, method was to locate the geometric path of the x-ray beam by the large concentration of tracks which started on this line and then the end of the track which lay in this path was the origin. In nearly all of the 174 stereoscopic pairs taken, the lead slits limited the x-ray beam to a cross section of about 1.5 by 0.5. mm. so that this gave a very sharp line containing most of the origins. Further, although most photoelectron paths show a small sphere, or dot, at both ends, of practically the same appearance, the section of track adjacent to the dot at the origin is nearly always less dense (showing less ionization) than the corresponding section near the end. This fact often aided in distinguishing the origins. After locating the origin of a given track the carriages were slid over the bed plate, and with respect to one another by the screw, until the cross hair appeared to cut through the origin. This setting, as all others, could be checked for accuracy by alternately closing each eye and ascertaining if the respective cross hair under the open eye was set above the corresponding point in each plate. However it was found that after some practice and adjustment of one's eyes, the setting could be made as accurately with the stereoscopic vision as by the slower "eye by eye" method. Scales A and B and drum C were read for the origin, and similar readings for a second point chosen on the path at the first bend. Obviously the difference between the corresponding readings were proportional to the three components of the path at right angles to each other. In order to obtain the actual components the instrument was calibrated by photographing two foot rulers, with sharpened metallic edges, clamped one in back of the other so that the edges, as measured by a traveling microscope, were separated 0.542 cm. These were placed at a distance in front of the camera equal to the distance of the x-ray beam. By measuring, on scale B, the distance between each inch mark on the rulers, the demagnification of the photograph was obtained directly and was found to be 3.52 and furthermore was constant in value across the entire 10 inches of the chamber's diameter. Likewise by setting, by stereoscopic vision on corresponding division points on each ruler, the divisions on the drum were evaluated at each inch point across the diameter of the chamber. Each drum division was equivalent to 0.226 mm. in depth and was constant across the diameter of the chamber; after practice, the settings could always be repeated to within 1.5 divisions. Thus the depth readings were made to 0.34 mm. and the width and height to 0.1 mm.

Having now obtained the components of the initial part of the track it is a perfectly straightforward calculation to obtain the angle with respect to the x-ray beam.

Before experiments were begun the lead colimating slits on the box enclosing the x-ray tube, were carefully lined up with a diameter of the chamber. The line connecting the two camera lenses was in the same vertical plane as this diameter. This caused the x-ray beam to pass parallel to the plates and perpendicular to their long side so that the direction of the incident x-ray beam was parallel to the motion of the carriages in the stereocomparator.

The best photographs to measure were those containing about eight to ten tracks. More than this number overlapped so much that the photograph was almost useless, as far as accurate measurements were concerned. On the 174 pairs of photographs there were measured 434 separate photoelectron tracks. Of this total 231 were in argon, 123 in air, and 91 in hydrogen. The intial pressure in the chamber varied slightly from day to day but was always between 60 to 65 mm. of mercury. The expansion ratio was not determined exactly, as it was chosen so as to give the most distinct tracks, but was about 1.3.

RESULTS

The results of measurements of tracks produced in

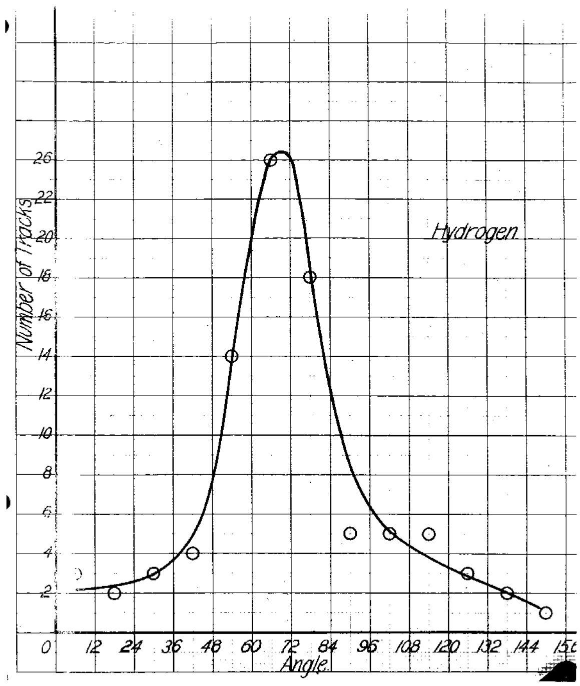


Fig. 5.

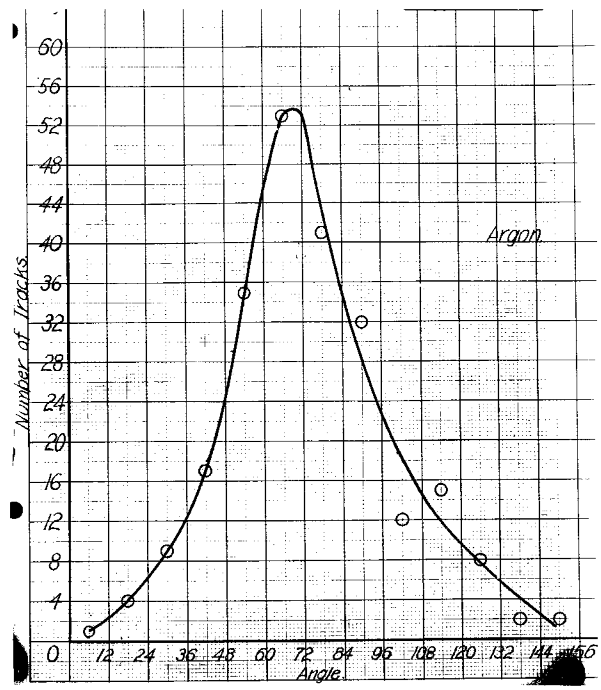


Fig. 6.

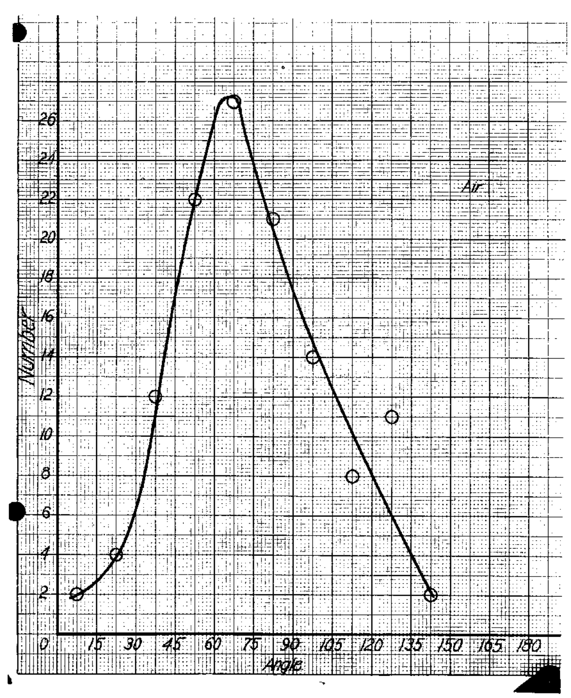
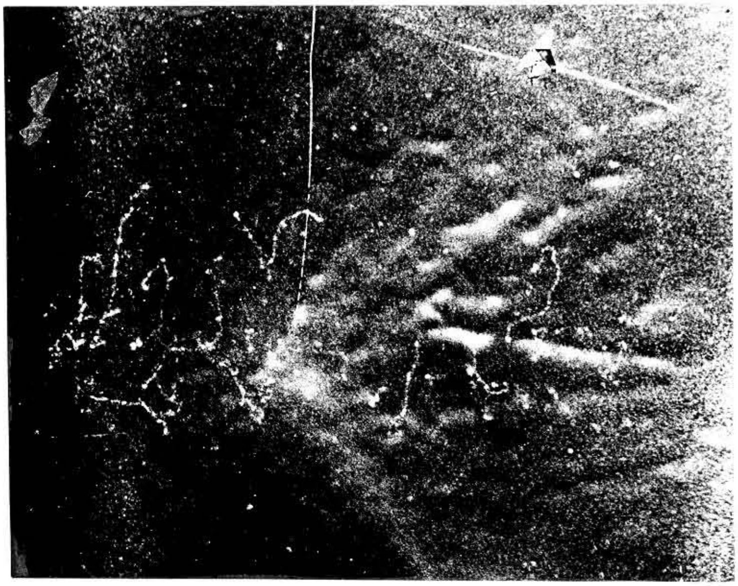


Fig. 7.

hydrogen, air, and argon under similar conditions, by the Ka line of Mo are shown in figs. 5, 6, and 7. The homogenity of the radiation was obtained by filtering that produced by a Mo target Collidge tube through a Zr oxide filter especially prepared for this purpose by the General Electric Co. The cross section of the beam was about 1/4 sq. mm.

The abscissa of these curves is the angle between the initial portion of the B-ray track and the forward direction of the x-ray beam. The ordinate gives the number of tracks found to start out within the chosen angular interval. (i.e. From fig. 5 it is seen that 26 tracks in hydrogen started out making angles of between 60 to 72^{o} with the forward direction of the x-ray beam.) Practically the same maximum is obtained if the angular intervals chosen are 10^{o}, 12^{o}, 15^{o}, 30^{o}, or 45^{o}, but the smaller intervals give points whose values are too much affected by the statistical fluctuations and the larger intervals give too few points to insure a clear curve. The 12^{o} and 15^{o} intervals chosen show the effect fairly and clearly.

The curves show clearly that the most probable direction of emission is in a direction at about 70^{o} with respect to the x-ray beam for all three of the gases studied. However it is to be remembered that since the absorption coefficient is proportional to the fourth power of the atomic number that very probably all of the tracks dealt with in the case of hydrogen actually arise from heavier gases (O_2) which are present as impurities.



These results agree very closely, as to direction of emission with those reported by other observers, (see bibliography) except in the case of Kirchner who reports the most probable angle of emission for photoelectrons to be almost exactly in the plane of the electric vector. Since the method of measurement which he uses is not clearly stated by Kirchner it is difficult to evaluate the accuracy of his work.

From the present work, in which the measurements on a given track can be rechecked to within about 4°, and the work using a Geiger counter by Bothe[4], there is little doubt but that there is a very appreciable forward component present in the majority of the tracks.

DISCUSSION.

The tendency toward ejection at right angles to the direction the incident radiation is in accord with the classical theory which would demand that all of the tracks start initially in the plane of the electric vector for unpolarized rays and in the direction of the electric vector for polarized rays. Since this last phenemena has been observed by Bubb the classical theory would seem to be satisfactory were it not for the presence of the forward component. By allowing the momemtum of the incident radiation in the forward direction to be passed on to the electron absorbing the energy, a shift of the peak forward to about 82° becomes theoretically possible. This however does not appear to be quite enough. Further the distribution of directions on either side of the most probable direction is not accounted for by these conceptions.

This distribution may be qualitatively accounted for by vectorially adding in the random momentum of the electron in its orbit, as has been shown by Bothe, but a more satisfactory explanation would appear to be that recently put forward by E.C.Watson (Phys. Rev. Vol. 29,752, 1927) which accounts for the spread of directions upon the basis of scattering and leads to a distribution function which fits the facts better than do any of the more elaborate theories.

In conclusion I desire to express my warm appreciation for the inspiration and guidance given me during the progress of this work by Professor R.A. Millikan; and to Dr. A.W. Simon for the help he has given in the design of the expansion chamber.

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