The Occlusion of the Residual Gas and the Fluorescence of the Glass Walls of Crookes Tubes.

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In a previous paper on the first part of this subject,* the writer has described experiments indicating that the occlusion of the gas is due, at any rate in some instances, to the gas being mechanically driven into the glass, in which it forms bubbles on the glass being heated strongly.

Since this paper was published, several comments on the writer's conclusions have appeared, and these have led to the writer making further experimental investigations which it is one of the purposes of this paper to describe.

In a lecture on March 16, 1907, at the Royal Institution,† Prof. J. J. Thomson suggested an explanation of the considerable depth from the inner surface of the glass at which the bubbles occur. This depth, as measured by the writer, amounts in some cases to more than one-tenth of a millimetre, which is a considerably greater distance than cathode rays are found to penetrate through aluminium. Prof. J. J. Thomson pointed out that both glass and silica have been shown to be permeable to hydrogen and helium at high temperatures, so that the effect in question might arise from the cathode ray bombardment raising the temperature of the surface of the glass sufficiently to permit of these gases penetrating by ordinary diffusion.

Again, in a paper entitled "The Formation of Gas Bubbles in the Walls of Heated Discharge Tubes," read before the German Physical Society on June 28, 1907,‡ Mr. Robert Pohl disputes the contention of the writer that the gas is driven mechanically into the glass, and maintains that the formation of the bubbles is entirely due to the presence of films of aluminium disintegrated from the electrodes and to chemical action connected with the oxidation of this aluminium when the glass is heated in a flame.

Finally, Mr. Frederick Soddy and Mr. Thomas D. Mackenzie, in their paper on "The Electric Discharge in Monatomic Gases," read before the Royal Society, November 7, 1907,§ from experiments made on argon, neon, and

* "The Occlusion of the Residual Gas by the Glass Walls of Vacuum Tubes," 'Roy. Soc. Proc.,' A, vol. 79, pp. 134—137.

† See 'Engineering,' March 22, 1907, p. 387.

‡ 'Berichte der Deutschen Physikalichen Gesellschaft,' pp. 306—314.

§ 'Roy. Soc. Proc.,' A, vol. 80, pp. 92—109.

helium spectrum tubes, seem to have come to the conclusion that the gas which causes the bubbles is not the residual gas in the tube, but is gas generated by chemical decomposition of the glass under the influence of local heating produced by the discharge, which heating in the case of their particular tubes was probably very considerable.

First of all, to deal with Mr. Robert Pohl's conclusions, as the writer's previous experiments did not at all bear these out, it was decided to make a crucial experiment in which there would be no possibility of the presence of any aluminium within the tube. For this purpose a vacuum tube was constructed as shown in fig. 1, the electrodes consisting of two caps of tinfoil, A and B, pasted on the outside of the tube. The tube was pumped up to a vacuum at which it gave green fluorescence. Alternating current at about 7000 volts was employed, this giving a current of 1 to 2 milliamperes, which was found to be as much as the tube would stand without getting warm.

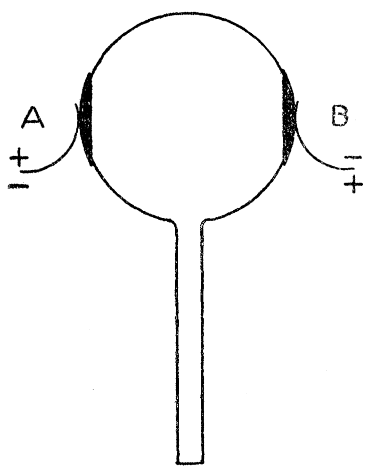

Fig. 1.

After sparking for 7½ hours the tube was broken up, when it was found that on portions of the glass being strongly heated in a blowpipe flame they immediately became filled with large numbers of very small bubbles. These bubbles were on the average about half the diameter of those observed by the writer in his previous experiments with tubes containing internal electrodes, and were also much nearer the surface of the glass, the depth being only about 0·025 mm. as against the 0·122 mm. measured in the case of the previous experiments. These variations are no doubt due to the fact that with tubes with external electrodes only very weak electrical discharges can be obtained, and the bombardment consequently is much less violent. These experiments, which were repeated several times with different tubes, always with similar results, appear entirely to dispose of Mr. Pohl's contention that the presence of a film of aluminium, or for that matter of any other metal, on the inside surface of the tube is in any way requisite for the production of the bubbles.

Furthermore, it was found that boiling the glass of these tubes with external electrodes in strong nitric acid, prior to heating in the flame, did not prevent the formation of the bubbles except in one case in which, after sparking for a number of hours, the interior surface of the tube was found to be covered with a brown film which was dissolved away by the boiling nitric acid, after which process no bubbles could be obtained in the glass. The writer is indebted to Mr. J. Thomas, of Faraday House, for making an analysis of this brown deposit, from which it appears that it consisted of carbon, due, as the writer has since ascertained, to volatile portions of the grease used in a stopcock on the pipe employed for exhausting the tube. It would appear, therefore, that when there is a sufficient deposit of this nature the occlusion takes place in the deposit and not in the glass as it does when no deposit is present.

Next, experiments were made with a view to ascertaining whether under the bombardment the gas is driven into the glass to as great a depth as that at which the bubbles appear on subsequent heating.

In all cases, whether internal or external electrodes were employed, it was found that grinding away the interior surface of the glass to a sufficient extent prevented any formation of bubbles on subsequent heating, and by just grinding to the extent necessary for this purpose and measuring the thickness of the glass before and after grinding, it was possible to estimate the distance which the gas had travelled into the glass under the bombardment, prior to the heating of the glass in the flame.

In specimens of glass from different tubes this distance was found to vary from 0·0025 mm. with external electrodes to as much as 0·015 mm. with internal electrodes, the differences being no doubt due to the varying velocities of the cathode rays, but in all cases this distance was found to be considerably less—usually in the ratio of about 1 to 10—than the distances between the surface of the glass and the centres of the bubbles produced by heating in the flame. From this it would appear that the gas travels considerably further into the glass when the latter is strongly heated.

As difficulties were met with in making accurate measurements owing to the curvature and irregular thickness of the glass of the tubes, in some of the experiments a piece of flat microscope cover glass, laid inside the tube in a position where the bombardment would reach it, was employed instead of the walls of the tube itself. As regards the penetration of the gas and the production of bubbles, this cover glass was found to behave exactly like the glass of the tube. It was also found that the depth of the bubbles in the glass could be very easily determined by examining the glass edgewise in a microscope. Observations made in this way showed that the bubbles, though in one layer, are usually at by no means a uniform depth.

Experiments were also made to ascertain what is the maximum distance that cathode rays will penetrate aluminium. For this purpose a small fluorescent screen of Willemite was placed behind a patchwork screen of aluminium foil, the four patches into which the latter was divided being composed of two, three, four, and five thicknesses respectively of aluminium 0·0028 mm. in thickness. The whole was placed in a tube opposite a flat cathode, so that the rays could only reach the Willemite after passing through the aluminium. With this arrangement it was found that the five thicknesses of foil gave about the limit through which the cathode rays would pass, at any rate sufficiently to cause fluorescence, the amount of fluoresecence obtained through the five thicknesses being exceedingly feeble, and only visible at all with cathode rays of a very active description.

From this it appears that the maximum thickness of aluminium through which cathode rays can ordinarily be made to pass in any quantity is about 0·014 mm., which, as the density of aluminium is 2·7 and that of glass about 2·47, agrees very fairly closely with the figure of 0·015 mm., which, as mentioned above, was found to be the maximum distance that the gas penetrated into the glass before heating sufficiently to form bubbles on subsequent heating in the flame.

It should be mentioned that in the experiments already alluded to on the tubes with external electrodes, the electric discharges passing through the tubes were so weak that the heating of the glass was very slight, the temperature of no portion of the exterior of the tubes exceeding that of the surrounding atmosphere by more than a very few degrees. Even after allowing for the fact that the instantaneous temperature of the interior of the tubes during each discharge would be higher than the mean temperature of the exterior, it does not seem possible that the temperature can have been sufficiently raised either to allow of the gas passing into the glass by ordinary diffusion, as suggested by Prof. J. J. Thomson, or to have caused the gas to be evolved inside the glass by chemical decomposition due to heat as put forward by Mr. Soddy and Mr. Mackenzie.

Furthermore, neither of these explanations seems really necessary, for, as has been shown, the gas in the first instance travels into the glass only about the same distance that cathode rays can be made to pass through aluminium, and it is therefore reasonable to suppose that the gas may be driven in mechanically. Diffusion, however, probably plays an important part in the final result, taking place at the later stage when the glass is softened in the flame. Under its influence, and also, perhaps, under that of surface tension, the gas then travels much further into the glass and forms bubbles at the moment of solidification, in much the same way that air dissolved in water forms bubbles when the water is frozen into ice.

No doubt where there is considerable deposit on the glass of aluminium from the electrodes, of platinum or of other material employed from the anticathode, or of carbon as above instanced, the occlusion may take place largely in such deposit, but otherwise the above experiments seem to bear out the writer's original conclusion that the occlusion is due to the gas being mechanically driven into the glass itself.

Experiments were also made in order to discover whether the penetration of the gas into the glass has any bearing on the fatigue of the latter in respect to fluorescence, discovered by Sir William Crookes nearly thirty years ago.*

In many cases this fatigue, according to the writer's observations, is due to deposits of aluminium or other electrode matter or of carbon on the glass, barely noticeable deposits having a marked effect in this respect. In other cases, however, fatigue shows itself where the most careful examination can find no evidence of such deposits, or after they have been removed, and where the cause of the fatigue must therefore be sought elsewhere.

In order to investigate the matter, a strip of glass was mounted in a tube opposite to a flat aluminium cathode, with a screen consisting of a strip of sheet iron considerably narrower than the strip of glass placed between the cathode and the glass, so as to shield a central zone of the latter from the bombardment. The iron screen was hinged at the end where it was supported, so that by means of a magnet it could be moved out of the way so as to allow the whole of the glass strip to be uniformly bombarded when required.

The tube was exhausted to a state in which the glass fluoresced brightly, and with the iron screen in position to shield part of the glass strip, the latter was subjected to vigorous bombardment for some seven hours. At the end of this period the bombarded glass showed very considerable fatigue, and when the iron screen was moved so as to allow the cathode rays to strike the whole surface, fluoresced much less brightly than the portion that had been shielded. Furthermore, the fatigue of the glass was found to be permanent to the extent that it had not perceptibly diminished after a rest of some sixteen hours.

The glass strip was next removed from the tube, and after its thickness had been carefully measured with a microscope a layer of wedge section of part of the bombarded surface was removed by grinding. On replacing the strip in the tube, and again subjecting the whole of it to bombardment, it was found that part of the strip where most glass had been ground off now showed no signs of fatigue, and fluoresced as brightly as the portion that had been screened from the initial bombardment, while those parts off which only little glass had been ground, or none ground off at all, still

* 'Phil. Trans.,' 1879, part 2, p. 645.

showed the fatigue, there being a well-defined line of demarcation between the fatigued and non-fatigued portions. On again removing the glass from the tube and measuring in the microscope its thickness at this line of demarcation, and comparing the figure with that of the original thickness of the glass, it was found that the thickness of the glass that had been removed at this point was 0·017 mm., this being the amount of glass that had to be ground off in order to do away with the fatigue. The experiment was repeated several times with both longer and shorter periods of bombardment, but always with similar results, the measurements varying but little. Also it was found to make little difference whether a separate piece of glass mounted in the tube, or a bombarded portion of the walls of the tube itself, were employed for the experiment. As will be observed, the figure of 0·017 mm. approximates very closely to the 0·015 mm., which, in tubes with internal electrodes, was the distance that the gas was found to be driven into the glass by the bombardment in quantities sufficient to form bubbles on subsequent heating.

Furthermore, experiments showed that glass which had been well bombarded by cathode rays so as to be greatly fatigued, and off a portion of which a layer had been ground of just sufficient thickness to restore the fluorescence of that part to the original brilliancy when tested under further bombardment, evolved bubbles under subsequent heating in a blowpipe flame only in those parts which had not been ground down sufficiently to remove the fatigue, the line of demarcation between those portions of the glass that gave and did not give bubbles on heating being very nearly though not quite identical with that between the portions that did and did not show fatigue. In each case the want of identity between these lines of demarcation showed that a slightly greater thickness of glass must be removed to do away with fatigue than is sufficient to prevent the formation of bubbles. This seems natural, as fluorescence under cathode ray bombardment is a surface effect, and it does not therefore signify so far as it is concerned whether the layer permeated by the gas is thick or thin; whereas for bubbles to be formed on heating, the gas must probably be located in the glass at not less than some definite minimum mean depth, at less than which the gas merely escapes when the glass is heated.

From the above it would appear, in some cases at all events, that the fatigue of the glass is intimately connected with, and is perhaps the direct result of, the penetration of the gas, for, as should be pointed out, the thickness of the layer of fatigued glass is quite considerable, and much greater than that of any surface deposits of carbon or of aluminium which, as already mentioned, have also the effect of diminishing the brightness o the fluorescence, and are, partially at any rate, in some cases the cause of fatigue.

The further suggestion that the fatigue may be due to the actual presence of the gas in the glass may help to explain the permanent nature of the fatigue where there is no carbon, aluminium or other deposit, for, as mentioned in his previous paper referred to above, the writer obtained bubbles in portions of the walls of a tube due to gas which had been imprisoned in the glass for some nine years. That the fatigue is very permanent is further borne out by the fact that the writer finds that the glass of a Crookes tube containing a hinged aluminium cross, of the usual description for showing this fatigue phenomenon, which has been lying unused since the year 1898, is still sufficiently fatigued by the bombardment it received ten years ago to show quite distinctly the usual appearance of a bright fluorescent image of the cross on a less bright background when the glass is uniformly bombarded, though no signs of any discoloration due to deposition of carbon or of aluminium or of other effect on the glass are visible by ordinary light. Though some portion of the fatigue effect is permanent, the remainder, which as a rule is the larger part, is but temporary. This may be due to the gradual escape of such portion of the gas as has been driven into the glass only such a very short distance that the latter is unable permanently to retain it.

The writer is again indebted to Mr. J. C. M. Stanton and Mr. R. C. Pierce for their assistance in carrying out the experiments.