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XXIX. *Experimental Determination of the Law of Reflexion of Gas Molecules.* By R. W. WOOD, *Professor of Experimental Physics, Johns Hopkins University* *.

[Plate III.]

VARIOUS phenomena connected with the flow of gases have led us to assume that the gas molecule, on collision with a solid wall, is reflected at an angle which is quite independent of the angle of incidence, and that the number reflected in any given direction is proportional to the cosine of the angle which this direction makes with the normal to the surface. This law is assumed by Knudsen in his recent treatment of the kinetic theory, but so far as I know it has never been verified directly by experiment. Some eight or ten years ago I made some efforts to realize what might be termed a one-dimensional gas by allowing the gas to enter a long highly exhausted tube through a very minute hole while in communication with a small bulb, which was broken after the system had been for some time in communication with the pump. It was assumed that the first molecules to reach the far end of the tube would be moving in parallel paths, and the electrical behaviour of such a gas was the phenomenon studied, the tube being non-conducting initially. As no very definite results were obtained, it is not worth while to record the details of the experiment. Attempts were also made to realize a one-dimensional gas by vaporizing mercury in a tube, a portion of which was cooled by solid carbonic acid, but these experiments gave also negative results. The very interesting observations of L. Dunoyer on the formation of sharply defined deposits of metallic sodium in highly exhausted tubes, due to the projection of a flight of molecules down the tube, led me to repeat my earlier experiments with mercury.

M. Dunoyer had pointed out to me the necessity for employing a very perfect vacuum, and after one or two experiments I had no difficulty in observing the phenomenon with mercury. In fact, mercury appears to be better adapted to the production of the one-dimensional gas than sodium, for the latter contains occluded hydrogen, and the last traces of this can be removed only with great difficulty, if at all. This gas impairs the vacuum very rapidly, and gives rise to deposits with ill-defined edges as a result of molecular collisions.

* Communicated by the Author.

The first experiment was made with a tube of the form shown in fig. 1 A. A droplet of mercury was placed in the bulb and the tube highly exhausted, the walls being heated with a Bunsen burner. After the occluded gas had been driven from the wall, the tube was allowed to cool, and the bulb heated until all of the mercury had distilled into the cooler portion of the tube. It was then sealed off from the pump, the capillary being heated very gradually, so as to have it at a temperature just below the softening point of the glass for some minutes before it finally collapsed. The mercury was now gathered into a single drop which was brought into the narrow neck of the tube. The whole was then introduced into a flask of liquid air with the exception of the turned-over neck. At the end of twelve hours a faint circular deposit of mercury, of the same diameter as the constricted portion of the tube just above the bulb, was observed. In this case the distillation had taken place at room temperature. The tube was now wound with insulated german-silver wire from a point just above the surface of the liquid air, to the closed tip. This was heated electrically to a temperature which felt uncomfortably hot to the finger. Under these conditions the phenomenon is reproduced in a minute or two. The mercury vapour enters the upper portion of the tube, and all of the molecules which are moving sideways are condensed on the wall, the deposit being very heavy at the top of the tube, and gradually thinning away to nothing a few centimetres below the surface of the liquid air. Below this point the molecules are moving all in the same direction, like bullets from a machine gun, and no further deposit is found until the constricted portion of the tube is reached. Here the molecular stream strikes the sloping walls of the constriction, and a heavy deposit of the metal occurs. Passing through the small opening, the gas traverses the exhausted bulb in the form of a jet which shows no tendency to spread out laterally, and deposits on the wall in the form of a small circular patch with very sharply defined edges (fig. 1).

A photograph of the deposit, formed on an oblique plate of glass within the bulb, is reproduced on Pl. III. fig. 1. In this case the tube was kept in liquid air for some time before starting the vaporization, to allow the plate to take up the low temperature.

In the study of the reflexion of the jet the reflecting surface must be kept at a relatively high temperature, to prevent the condensation of the vapour. A large drop of glass was ground off at an angle of 45° , and the oblique

surface polished with rouge on pitch. The drop was mounted on a slender stem of glass which was fused to the bottom of the drawn-out portion of the bulb (Pl. III. fig. 2). In this case the deposit began to appear in about three minutes

Fig. 1.

after the heating-current had been started, and in ten minutes it was so opaque as to be quite impervious to light. As will be seen from the photograph, the deposit covers the

upper oblique half of the bulb with the exception of a narrow circular zone just above the plane of the plate.

This clear zone is extremely interesting.

I at first attributed it to the circumstance that the diameter of the bulb was small in comparison with that of the reflecting surface. To test this hypothesis the experiment was repeated with a larger bulb, and a deposit as shown in fig. 3 was obtained, in which the cosine law and the random direction of reflexion are well shown. Professor Max Mason, of the University of Wisconsin, made a calculation of the distribution of density in a bulb small in comparison with the reflecting surface, which by the way is not an easy problem, and found that the clear zone was not accounted for on this supposition. I then repeated the experiment with the large bulb, and found that, if the deposit was allowed to form for fifteen or twenty minutes, the clear zone was quite as marked as with the smaller bulb. It occurred to me that the clear zone might have something to do with the structure of the surface, irregularities of molecular size perhaps preventing the nearly grazing reflexion. I tried a freshly split surface of mica mounted on a glass plate, and obtained the deposit shown in fig. 4, the clear zone being quite as conspicuous as with the glass surface.

Dr. Wright, of the Geophysical Laboratory, informs me, however, that some experiments which they have made, suggested by the account of my experiments which I gave at the Spring meeting of the National Academy, have yielded quite remarkable results in the case of the reflexion from the surfaces of certain crystal sections. An account of these experiments will be published shortly.

In the reflexion experiments the reflecting surface keeps the temperature which it had before the immersion of the apparatus in liquid air, as it is isolated in a non-conducting vacuum, and the only escape for the heat is through the long thin stem which supports it. In some cases I heated the bulb while it was still full of air, and in this way brought the reflecting surface to a rather high temperature before the exhaustion was commenced. The tubes were usually provided with a lateral branch, joined on midway between the two constrictions and bent up. The exhaustion was effected through this tube, and it was found advantageous to keep the pump in operation throughout the course of the experiment.

The results appear to show that the cosine law is approximately followed, for the density is greatest on the line of the normal, falling off gradually as the angle increases. At

angles greater than about 80 degrees there appears to be no reflexion, at least in the case of the two surfaces which I have examined.

The jet of molecules obtained in this way is interesting in that both the temperature and pressure are vector quantities.

Molecular collisions have been completely abolished and the lateral pressure is zero. The same may be said of the temperature I suppose, though we must specify what we mean by temperature in such a case.

An experiment was made to determine whether the jet was capable of rendering its path conducting. The lower constriction was made rather large, and a platinum wire sealed in so as to lie across the path of the jet, which played upon another electrode at the bottom of the bulb. The bulb was non-conducting, and no visible discharge occurred when the jet was started. It is possible, however, that experiments more carefully carried out, on the electrical properties of a one-dimensional gas, might yield interesting results.

It is my intention to illuminate the jet with the light of the 2536 mercury line, and determine the molecular velocity by the displacement of the resonance radiation line.

It may very well be that interesting results can be obtained with an apparatus in which the reflecting surface can be held at any desired temperature, for example at a temperature a hundred degrees or so higher than the temperature at which the mercury vapour is liberated. Possibly some information can be obtained in this way as to the nature of the molecular agitation which we call heat. It is obvious that the reflexion of the molecules results solely from this agitation, since, if we remove the heat from the reflecting body, reflexion no longer occurs and the molecules remain fixed to the wall. It will also be interesting to work at a temperature intermediate between that at which complete reflexion occurs, and that at which complete condensation takes place. Experiments along these lines will be undertaken in the autumn.

I have not tried projecting the phenomenon, but see no reason why it could not be done with a form of apparatus similar to that shown in fig. 1 of the Plate. The success of the experiment would depend largely upon whether the heat rays which are absorbed by liquid air could be removed from the beam of the lantern.

FIG. 1.

FIG. 2.

FIG. 3.

FIG. 4.