A suspected case of the Electrical Resonance of Minute Metal Particles for Light-waves. A New Type of Absorption

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DISCUSSION.

Prof. S. P. THOMPSON exhibited some tellurium mirrors made in the same way as the selenium ones used by Prof. Wood.

XIII. *A suspected case of the Electrical Resonance of Minute Metal Particles for Light-waves. A New Type of Absorption. By R. W. WOOD, Professor of Experimental Physics in the Johns Hopkins University*.*

CERTAIN experiments on which I have been engaged of late have led me to believe that I have found a new type of light absorption, which it may be possible to refer to the electrical resonance of small metallic particles for waves of light. The experiments of Garbasso and Aschkinass have shown that a plate of glass covered with uniformly arranged strips of tinfoil of equal size, which serve as resonators, shows the phenomenon of selective transmission and reflexion for electromagnetic waves of different wave-lengths. In other words, a plate of this description exhibits the electrical analogy of surface-colour. I have succeeded in producing metallic deposits on glass which the microscope shows to be made up of particles smaller than the wave-lengths of light, which by transmitted light exhibit colours quite as brilliant as those produced by aniline dyes. I have sought in every way to explain these colours, by all the well-known principles of interference and diffraction, and at the present am forced to accept the hypothesis suggested in the title of this paper, which I have chosen not without some misgivings.

In the present paper I shall content myself with giving a full account of the experimental data which I have thus far obtained, postponing for the present anything like a definite conclusion.

The metallic deposits are obtained by heating small fragments of the alkali metals in glass bulbs, thoroughly exhausted and hermetically sealed. Only the small portion of the bulb on which the metal particle lies is heated, leaving the

* Read March 14, 1902.

remainder, where the condensation is to take place, quite cold. The metallic film which condenses on the wall, when viewed by transmitted light, shows colours of excessive brilliancy, as brilliant in fact as films strongly stained with aniline dyes. On first obtaining these films, I was of the opinion that these colours could be attributed in some way to interference, but more careful consideration showed that many difficulties were present. In the first place, the transmitted colours, in the case of thin plates, are never of any considerable intensity, being diluted with a large excess of white light. Moreover, the extraordinarily high absorption-coefficient of metallic sodium makes it impossible for us to apply the theory of the colours of thin plates, except on the assumption that the thickness of the film is exceedingly small in comparison with the wave-length, and that there is a relative change of phase at the two surfaces, which varies with the wave-length. This seemed on the whole not very probable, for, as far as experiments go, indications are that the phase-change in metallic reflexion is nearly independent of the wave-length. Moreover, metallic films obtained in other ways, as by chemical or cathodic deposition, do not show these colours. Thin films of metal show a more or less marked colour by transmitted light, but the colour is fixed for any definite metal, and, except in the case of gold and silver, not very pronounced. The sodium films, on the contrary, may be deep purple, blue, apple-green, or red according to conditions. I noticed at the outset that where the deposit was somewhat dense in the immediate vicinity of the sodium drop, the outside of the bulb, seen by reflected light, exhibited halo effects, similar to those shown by certain minerals. This pearly or silky lustre, which is difficult to describe, I at once recognized as a diffraction effect due to the scattering of light by small reflecting particles. Examination under the microscope showed this to be the case, the sodium having deposited on the glass in the form of small isolated drops. It at once occurred to me that the condition might be the same in the coloured films, the particles here being small enough to respond to the light-waves, in the same manner as the resonators of Garbasso and Aschkinass. I examined some of the more transparent of the coloured films, under a one-twelfth inch oil-immersion

objective, and found that my suspicions were verified, the films being made up of particles just barely visible as individual grains lying close together. I was unable to satisfy myself that the size varied with the colour of the film, and am of the opinion that if the resonance theory is the true one, the free period depends more on the proximity of the particles than on their actual size. The diameter of the particles, as measured with the micrometer, varies from about $\cdot 0003$ to $\cdot 0002$ mm. In other words, they are of about the size of the smallest micrococci described by the bacteriologists.

It occurred to me at first that the colours might be similar to those shown by mixed plates, which are explained in the same way as the coloured central images seen in certain transparent diffraction-gratings. This would, however, necessitate the presence of minute transparent particles of a thickness sufficient to give a retardation of $\lambda/2$. The formation of such particles could be conceived of as resulting from the oxidation of the sodium particles by a layer of absorbed air on the glass. It is therefore necessary to show at the outset that the cause of the colour is the presence of metallic sodium. That this is the case I feel sure, for if the slightest trace of air be allowed to enter the bulb, the colour, no matter how intense, instantly vanishes, the glass becoming as clear as before the formation of the film. The oxidation process could be made to take place slowly, by drawing out one end of the bulb into a long fine capillary, with a bore of about $\cdot 01$ mm., and breaking off the end after the coloured film had been formed.

In certain cases it was observed that the colour changed before disappearing entirely. I also found that the colour of the film could be permanently changed by carefully heating the glass to a temperature just below that necessary to evaporate the film. Local heating to a slightly higher temperature drives off the film entirely, leaving the glass perfectly clear. By means of a small flame, it is possible to drive a patch of colour all over the inside of a bulb, and it is in this way that some of the best films are prepared. It was next found that cooling the films by the application of ice to the exterior of the bulb produced most extraordinary changes of colour. Pale green films, almost transparent, on being cooled ten or fifteen degrees, changed to a violet as deep as

that shown by dense cobalt-glass. Pink films were changed to deep blue-green, while films originally deep blue became transparent. These effects were most puzzling at first, but I finally succeeded in finding out the cause, as I shall show later on. At the beginning of the work it was almost impossible to predict what sort of a film would be obtained in any experiment. Sometimes, on first heating the sodium, a film of a deep claret colour would be obtained; once formed, it could be driven from one part of the bulb to another without any great change of colour. In another experiment, made under exactly the same conditions, so far as I could see, it was impossible to obtain anything but a deep blue. I prepared and experimented with fully fifty bulbs, without being able to arrive at any definite conclusion in regard to the conditions necessary for producing a definite result. It was finally found however, by blowing connected bulbs, that if the sodium was thoroughly boiled in one of them, and while still molten was shaken into an adjoining bulb, the surface of which was of course free from any deposit, on heating the globule in the fresh bulb, only blue films could be produced. This made it appear as if the claret-coloured film were produced by something volatile in the sodium which was driven off by the first heating. It was necessary, if possible, to find out what this was, for these red films were found to be more interesting than the blue, and it was desirable to be able to produce them at will. As a result of many experiments, I had formed a vague notion that bits of sodium cut from certain lumps in the bottle produced the red films on the first heating, while portions taken from other lumps did not. It seemed not unlikely that the sodium might contain potassium as an impurity, which might be the agent concerned. I accordingly prepared a set of bulbs containing potassium, and immediately found that magnificent reds and purples could be obtained at will; and I felt firmly convinced that the anomalies shown by sodium were due to potassium impurities. Similar coloured films could be obtained with lithium, though, owing to its higher boiling-point, bulbs of bohemian glass are required. Letting this serve as an introduction, it will be well to take up the experiments somewhat in detail.

As the optical behaviour of the films is extremely interesting, regardless of the ultimate cause of the colour, I shall describe in some detail the manner of preparing and filling the bulbs. It is in the first place a great economy of time if a number are exhausted at once. To accomplish this I have fitted the mercurial pump with a glass tube having half-a-dozen lateral branches drawn down as shown in fig. 1. The bulbs are

Fig. 1.

blown of the form shown in the same figure, and a piece of sodium or potassium is cut up under ligroin into blocks about 3 mm. on each edge. These are introduced into the bulbs as quickly as possible after wiping off the fluid, and the stems of the bulbs drawn down to a small bore for subsequent sealing.

They are quickly fastened to the branch tubes and exhausted. I find it a good plan to heat the metal until it fuses while the bulb is still on the pump; the whole bulb may be warmed by a Bunsen flame to drive off absorbed air. If the exhaustion is carried down to the point where the mercury begins to hammer, it is generally sufficient. The bulbs are now sealed off from the pump, and may be put away for future use, or experimented with at once. A burner should be made by drawing out a glass tube, which will give a pointed flame about half a centimetre high, and the tip of the flame allowed to play against the spot on the bulb where the metal lies (fig. 1, *a*). Sometimes the whole bulb will suddenly flash a deep violet or blue, and sometimes the film will develop more slowly. A chain of three or four bulbs may be made,

the sodium heated in one, and the clean molten metal shaken into the others, drops of various sizes sticking to the bulbs. Coloured films can then be formed by heating these clean drops in the bulbs. This shows that the oxide present in the first lump has nothing to do with the production of the colour.

I shall now take up in order and in some detail the appearances of the films by reflected and transmitted light, the spectral analysis of the light, the polarization effects, and the very remarkable temperature changes.

If the metal is heated at one end of a rather long tapering bulb, the colour is most intense near the metal and gradually fades away to nothing at the other end of the bulb. If the bulb is placed in strong sunlight with a black background, it is seen that in some places where the deposit is too slight to show much colour by transmission the light is scattered or diffused, and this diffused light is coloured. The claret-coloured or purple film, where the deposit is slight, scatters a green light, the surface appearing as if fluorescent. Now the spectrum of the transmitted light in these purple films has a heavy absorption-band in the yellow-green, consequently the scattered light is the complementary colour of the transmitted. If the film is greenish blue, the scattered light is reddish. The microscope shows that in these deposits, which have the power of scattering light, the individual particles are rather widely separated, that is, the distance between them is large in comparison to their diameters. I shall speak of this light as the "fluorescent" light, to distinguish it from the light scattered by the large particles, which is not coloured except by diffraction. This light, which gives the bulbs a slightly silky lustre where the particles are large, I shall call diffused light.

Returning now to the fluorescent light: in the case of the purple films, the appearance of a bulb in strong light is very much as if certain portions of its interior surface had been painted over with a solution of fluorescein. No trace of regular reflexion is shown by these films, except of course the reflexion due to the glass. The particles are so far apart that they apparently act as independent sources, the interference necessary for rectilinear propagation not being present. If the incident light is polarized, the fluorescent light is also

polarized, which is not the case for ordinary diffuse reflexion. On the resonance theory, we may regard this fluorescent light as the energy radiated from the resonators, as a result of their forced vibrations. Passing now to a part of the film where the colour of the transmitted light is deeper, we find that there is no longer any trace of this fluorescent light. The colour absent in the transmitted light is now regularly reflected, the particles being so close together that interference, as imagined by Huygens, takes place. In strong sunlight, this portion of the film shows neither the fluorescent nor the diffused (diffracted) light. Except at the spot where the regularly reflected image of the source of light appears, it is quite dark like the clear glass. Still farther down the bulb where the particles are very large, we get ordinary scattered light, and the film has the silky lustre to which I have alluded.

Summing up the results thus far, we find :—

Coarse particles diffract or scatter light, and give the bulb a silky lustre.

Minute particles very close together, regularly reflect those wave-lengths absent in the transmitted light, but give no scattered light.

Minute particles far apart, diffuse light of the same wave-lengths as those which are, to some extent, absent in transmitted light. This type of scattered light, which for convenience I have called fluorescent, is exhibited by deposits which are too scant to show any trace of colour when viewed by transmitted light.

Spectrum of the Transmitted Light.

An examination of the transmitted light with a small direct-vision spectroscope showed that in some cases the films completely refused transmission of certain wave-lengths. The claret-coloured films had an absorption-band in the yellow, which was exceedingly black and quite narrow, its width rather less than one tenth of the easily visible spectrum. Any theory accounting for the colour of this film must explain the complete extinction of certain wave-lengths. In the case of the blue films, the absorption-band was in the red, but in this case it invariably appeared more diffused. The

green films apparently absorbed, more or less completely, the blue and red ends of the spectrum.

The changes of colour which accompany change of temperature are of two distinct types: a permanent change usually the result of local heating, and a temporary change, the result of cooling.

I was much puzzled by the fact that the change in colour was in the same direction in both cases; the region of absorption appearing to shift in the direction of greater wave-lengths. Purple-red films, with an absorption-band in the yellow, changed to blue, the change being due to the shifting of the band into the red. The effect can be best observed by touching the outside of the bulb with a hot glass rod. A transparent spot then appears where the metal has entirely evaporated, surrounded by a blue ring on a purple field. Placing the slit of the spectroscope along a diameter of the ring, the spectrum appears as in fig. 2, *a*. With potassium films, I have sometimes obtained permanent changes in the opposite direction; a violet-blue film becoming pink when heated, the spectrum appearing as in fig. 2, *b*. I do not feel sure that I have determined the exact cause of the permanent colour-changes, due to heating. It doubtless depends on the partial evaporation of the metallic particles, and we

Fig. 2.

must bear in mind that the period of vibration depends, not only on their size, but on the distance between them; both of which quantities will be affected by evaporation. The matter is probably further complicated by the fact that, in some cases, I have had films made up of particles of two different sizes. In this case it is not difficult to imagine that the smaller ones are completely vaporized, while the larger ones, which previously were of too great size to produce

colour, are brought down to dimensions small enough to enable them to resonate. This might explain the change from purple to blue. Experimental evidence is, however, rather against this hypothesis; and for the present I prefer to leave the cause of the permanent change in colour an open question.

The changes produced by cooling are much more startling, and of greater interest, for the cause has been discovered. We may summarize these effects something as follows:—Pink and purple films become blue when cooled, the original colour returning as soon as they are warmed up again. A pale green film becomes deep violet, while in some cases I have found that films, originally blue, become almost perfectly transparent when cooled, the blue colour returning subsequently. These effects are best shown by touching the outside of the bulb with a small piece of ice. At first sight, it seems as if the only possible effect of cooling would be a slight reduction of the size of the particles, and a contraction of the supporting wall. That this should be sufficient to affect the period of their vibration was almost unthinkable. If it were so, a further lowering of temperature should produce further changes, but I found that it was quite immaterial whether the bulb was touched with ice, or with a mixture of solid carbonic acid and ether; the resulting colour being the same in both cases. I have frequently obtained films so sensitive, that merely moistening the outside of the bulb and blowing upon it was sufficient to produce the change. On wiping it, or on stroking the bulb with the finger, the original colour would return. This was strongly suggestive of a molecular change, and for a while I was inclined to regard it as analogous to the well-known case of iodide of mercury. The final solution occurred to me in the following way. I had been for some time endeavouring to introduce into the bulb some fluid of high dielectric constant, to determine its effect on the colour. All fluids tried apparently contained sufficient oxygen to instantly bleach the films. The introduction of such a fluid should, it seemed to me, increase the capacity, slow down the period, and shift the absorption-band towards the red, or perhaps out of the visible spectrum entirely. Films had often been obtained which showed

absolutely no trace of colour-change on cooling, and it occurred to me that possibly traces of hydrocarbon vapour, from the ligroin in which the metal had been kept, might be condensed on the wall by the application of a cold body. I first prepared some films from sodium and potassium which had been heated for some time *in vacuo*, in order to remove all traces of the hydrocarbon. These films were invariably unresponsive, to either ice or solid carbonic acid. I next made a double bulb, and formed a film in the usual way in one of the bulbs. This film proved to be exceedingly sensitive to the application of ice, changing from apple-green to the colour of dense cobalt-glass. I now packed the other bulb in carbon dioxide and ether, in order to condense in it all of the suspected hydrocarbon vapour. It was then found that the film was no longer sensitive to the application of cold. To make absolutely sure that the true cause had been found, I cooled a small spot on a pink film to a low temperature by means of a small piece of carbon dioxide, which was left on the bulb for some time. The spot became almost colourless, the absorption having passed entirely out of the spectrum. On examining the spot quickly under the microscope, I had no trouble in seeing minute globules of a transparent liquid, sufficient quantity having condensed to form droplets. These grew rapidly smaller as the glass warmed, and the instant they disappeared, or perhaps a fraction of a second afterwards, the field of the instrument became first bluish, then pink, in consequence of the entrance of the absorption-band into the spectrum again.

There is a temperature effect of a different nature, which at first seems wholly inexplicable, but which I now think I understand. On one or two occasions I have had potassium films, originally deep violet, become almost transparent on the application of cold, and remain so *permanently*. What was still more remarkable, the appearance of the spot viewed in reflected light indicated clearly that the size of the particles had been increased, the spot showing the silky lustre to which I have already alluded, while the film surrounding it scattered no light at all. I had noticed that these films were apparently made up of two sets of particles—one set large enough to be seen under a low power, the other only coming into view under the highest power obtainable. After the temperature

change, the smaller ones seemed to have disappeared entirely; and I am now of the opinion that the condensation of the fluid film enabled them in some way to gather about and adhere to the larger particles, building up aggregates large enough to diffuse light.

Changes produced by Oxidation.

If the tip of one of the bulbs is cut off, the entrance of the air causes the coloured film to vanish like a flash. In some instances, I was of the impression that I detected a momentary change of colour before the film disappeared. To lengthen the process, I adopted the expedient of drawing the end of the bulb out into a long fine capillary, with a bore less than one one-hundredth of a millimetre. In this bulb a film of a deep pink colour was formed, and on cutting off the tip of the capillary the colour changed to blue, and the film vanished almost immediately. The small amount of air necessary to efface the films is indicated by the fact that at the end of an hour there was still a fairly good vacuum in the bulb, notwithstanding the fact that the end of the capillary had been open all the while. If the mouth of the capillary is fused immediately after the oxidation of the film, a new coloured film can be formed by heating the metal, the oxygen having been removed by the first film. This process can be repeated a number of times, showing that the presence of the oxide on the glass does not interfere with the deposition of the coloured film. If the process of oxidation be made very slow, by employing a very long capillary, and the process watched under the microscope, the black particles slowly become dim, and finally fade away. I am of the opinion that the microscope merely shows us the diffraction-disk due to the opaque particle. This would become dimmer as the size of the particle is reduced, without any apparent change of size. Examination with the spectroscope shows us that, during the process of oxidation, the absorption-band sometimes moves out of the spectrum through the red end, and sometimes merely fades away without any motion. I have tried filling the bulbs with carefully dried hydrogen gas, after the film had been formed, but the traces of oxygen present in the gas were sufficient to bleach the films. By employing two adjoining

bulbs, each lined with a coloured film, and cooling one of these in carbonic acid and ether, I was enabled to fill the bulbs with hydrogen at atmospheric pressure without destroying the coloured film in the cooled bulb. The low temperature prevented chemical action, and the oxygen was wholly removed by the film in the warmer bulb. On warming the bulb again, the colours persisted, showing that no change was produced by the presence of pure hydrogen.

I find that it is even possible to fill a bulb with air at atmospheric pressure without destroying the colour, if the bulb is thoroughly cooled with the carbon dioxide and ether, the chemical action not taking place at this low temperature. These experiments were tried to test a certain theory of the cause of the colours which occurred to me one day, which it is not necessary to go into as it was found to be worthless. The extreme sensitiveness of these coloured films to minute traces of oxygen makes it seem probable that they will prove useful in the study of the flow of gases through small apertures and capillaries. I have noticed that if the capillary is exceedingly fine, the film, instead of disappearing all at once, gradually melts away, beginning at the end of the bulb near the capillary. Sometimes it is half-a-minute before the colour at the other end of the bulb bleaches out. It is as if a fluid were slowly rising in the bulb and dissolving the film. This seems rather surprising, in view of the ideas which we hold about the diffusion of gases in highly exhausted receivers.

Relation between the Colour of the Film and the Size and Distribution of the Particles.

One peculiarity of the coloured films is that the colour produced under a given condition seems to depend in some way on the condition of the glass surface on which the film is deposited. Circular pink spots are frequently found on a blue field, while sometimes circular spots quite devoid of colour are observed. The centre of the circle is usually occupied by a dark speck, which I believe to be a small particle of the metal thrown up when the globule is heated. This speck, strangely enough, seems to modify the nature of the surface of the glass over a circular area surrounding it, so that a film of a different colour forms on it, or in certain

cases no film at all forms. One of these spots which I studied under the microscope proved interesting. The black speck in the centre was found to be made up of a number of coarse particles of the metal lying close together. Surrounding this was a transparent ring, the particles here being very minute and very widely separated. Next came a ring of pinkish purple (absorption-band about at the D lines), while outside of this came a ring of deep blue (absorption-band in the red). The surrounding field was practically colourless, being made up of large particles similar to those at the centre of the ring (fig. 3). In the blue ring the particles were

Fig. 3.

distinctly closer together than in the pink one; a circumstance which I made sure of by having a number of other observers express an opinion on the matter. If now the particles are packed closer together in the blue film, we should expect the capacity to be increased, the same as by the introduction of the medium of high dielectric constant. The period would consequently become slower, and the absorption-band would lie further along towards the red, which is exactly what was observed. In some instances, I have been of the opinion that the particles in the blue films are larger than those in the pink ones, but of this I am not sure.

Behaviour of the Films with Polarized Light.

One of the first experiments which I tried with the deposits which were made up of particles large enough to scatter light, was their polarizing power. The angle of complete polarization in the case of non-metallic particles is 90° , as is well-known. J. J. Thomson (Recent Researches) has calculated the scattering effect of metallic spheres on light-waves, and has found that we should expect complete

polarization on a line making an angle of 120° with the direction of the incident light. I am not aware that any experiments have been made to test this calculation. The results which I obtained gave a value somewhat larger than this, the mean being about 135° . It is difficult, however, to get very accurate results with films deposited on spherical surfaces.

Very interesting results were obtained as soon as the coloured films were examined by polarized light. To enumerate all of the different effects which I have recorded in my note-book would require too much space, and I shall only mention two or three typical effects. The arrangement of the apparatus was as follows. The light of a Welsbach burner passed through a Nicol prism mounted in an opaque screen in such a way that it could be turned through a right angle, then through the coloured film at oblique incidence, and then into the direct-vision spectroscope. It was found in the case of one of the purple films, which had a strong absorption-band in the yellow-green, that this band was only present when the electric vector was parallel to the plane of incidence. When the electric vector was parallel to the surface the spectrum appeared continuous. In every case the colour was much more pronounced when the electric vector had a component normal to the surface. On turning the nicol from one position to the other, no motion of the absorption-band could be detected in this film, the change consisting in a gradual fading away. In other films, however, I have sometimes found that the absorption-band shifts its position when the nicol is turned. For example, in the case of a film which showed an absorption-band a little below the D lines with the electric vector perpendicular to the plane of incidence, on turning the nicol the band moved along into the red and became broader and fainter, the effect being similar to that produced by cooling the film.

When the films are viewed between two nicols more complicated effects are obtained, which I shall omit for the present as they have not yet been carefully studied.

Until someone has calculated the behaviour of a sheet of resonators at oblique incidence with reference to waves polarized in and at right angles to the plane of incidence,

it will be impossible to say whether the polarization experiments are in accordance with the resonance hypothesis or not. It seems to me, however, that the results obtained with polarized light will be the means of eventually determining the exact cause of the colours, or at least in deciding in favour of, or against, the theory of electrical resonance.

Electrical Conductivity of the Films.

The coloured films are apparently non-conducting. Inasmuch as it was difficult to make sure that the films were deposited up to and against the "sealed-in" electrodes, a bulb was fitted with a ground joint through which the wires passed as shown in fig. 4. After the film had been deposited the joint was turned, causing the tips of the wire to be drawn over the film. With a sensitive galvanometer in circuit with the bulb, 75 volts gave no deflexion when the wires were drawn over the film, though they scraped the glass clean of

Fig. 4.

the deposit. No change was produced in the appearance of the film between the wires with a potential-difference of 700 volts obtained from a storage-battery. With higher voltages a gas-discharge commenced, and the colour changed in the neighbourhood of the electrodes, owing to the heat. I have tried the effect of illuminating the films with the light of an arc brought close up to the bulb, but there is absolutely no trace of conductivity, even under these conditions. This is true even for deposits so dense, that under the microscope the particles appear to be in contact with, and even piled up on top of one another. A possible explanation of the absence of conductivity may be, that the granules consist of a metal core, surrounded by a non-conducting film of some sort, possibly oxide. I have noticed that bulbs, in which films have been repeatedly formed and driven off by the application of a flame, finally reach a state in which it is no longer possible to form coloured deposits, but I have not yet deter-

mined whether this is due to a modification of the surface of the glass, the removal of the oxygen, or some other cause. At the present time, I am studying the effects of the introduction of a small amount of liquid ligroin, which can be accomplished without impairing the vacuum, or destroying the coloured film, in the following way:—One end of the bulb is drawn out into a thin-walled tube with a bore of about 1 mm. After a satisfactory coloured film has been formed, a swinging motion of the arm drives the drop of molten metal down into the small tube, sealing it hermetically. The tip of the tube is then cut off under ligroin, which completely fills the tube, as far up as the plug. By means of a small flame, it is possible to close the mouth of the tube, the empty portion containing practically nothing but hydrocarbon vapour. On carefully warming the metal plug to the fusing-point, the hydrocarbon is discharged into the bulb, passing through the shell of liquid metal which adheres to the walls of the tube and removes from the fluid any impurities which are detrimental to the film. In this way, I have been able to introduce ligroin in quantities sufficient to thoroughly wet the inside of the bulb, and have obtained in this way colours of even greater brilliancy than before.

Conclusion.

At the present stage of the work, it seems to me that it is impossible to decide either in favour of, or against, the theory of resonance. Most of the changes produced by varying the conditions seem to be what we should expect. The idea of electrical resonance has, at all events, proved useful as a working hypothesis, for it led directly to the discovery of the cause of the changes produced by low temperatures. While I have obtained coloured films from sodium, potassium, and lithium, I have been unable to obtain them from thallium and cadmium, which give granular deposits very similar in other respects. I cannot help feeling that I shall eventually find some other explanation than the one ventured in the title of this paper, though I have been unable to conceive of any arrangement of media which will show colours of this nature by interference. At all events, it appears to me

that we have colour phenomena quite unlike any that are already known, and which are of some interest, regardless of the ultimate explanation which may be given them.

Baltimore, February 1, 1902.

DISCUSSION.

The Secretary read a letter from Prof. R. THRELFALL drawing the attention of the author to some experiments upon the same subject published by him in 1894. Particles of gold and platinum were deposited in a liquid, and good scattering of light obtained in all cases. The polarization-angle was exactly the same as with non-conducting particles. Prof. J. J. Thomson has shown that the peculiar scattering effect is only to be expected within very narrow limits as to size of particles. The colours observed by Prof. Wood should only be noticed when the particles have a very restricted size, and evidence in favour of or against the author's theory should be afforded by comparing the observed and calculated sizes of the particles. The value of the polarization-angle of the scattered light observed by Prof. Wood is evidence in favour of the theory suggested.

Mr. LUPTON pointed out that the experiments had probably been rendered difficult by the different colours in which the oxides of sodium and potassium can exist.

XIV. *The Thermal Expansion of Porcelain.*

By A. E. TUTTON, *B.Sc., F.R.S.**

THE thermal expansion of porcelain has formed the subject of several investigations during the last three years, and has become a subject of considerable importance in consequence of the employment of porcelain of the Bayeux and Berlin varieties for the reservoirs of air-thermometers.

The present investigation has been carried out with a specimen of Bayeux porcelain, which was kindly placed at the author's disposal by Prof. Callendar. It is of especial interest as being cut from the same tube which was employed (1 metre

* Read March 14, 1902.