77 John Tweedy

Science Lectures

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THE ABSORPTION OF LIGHT

AND THE

COLOURS OF NATURAL BODIES.

BY

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LECTURES TO SCIENCE TEACHERS.

THE ABSORPTION OF LIGHT AND THE COLOURS OF NATURAL BODIES.

BY PROF. STOKES.

LECTURE I.

This subject is one which does not admit very well of experimental illustration before a large class; in fact, with all the appliances of the electric light, I should only be able to show you, comparatively imperfectly, what you can each see for yourselves by experiments which you can make quietly in your own chambers, requiring, I may say, hardly any apparatus at all. The foundation of what I have to say rests on Newton's discovery of the compound nature of white light, with which I presume you are already familiar. You know that when a beam of light is allowed to fall upon a prism, it is decomposed into the different kinds of light of which it consists which are bent round in passing through the prism to a different degree.

Supposing a beam of sunlight reflected horizontally into a room through a small hole and allowed to fall on a prism close by, if the light were of one kind, the beam would be simply bent round as shown in this diagram [referred to], and instead of a circular spot being painted on the wall as at A, it would be as at B. But on making the experiment you have actually an elongated coloured image. The cause of that is, the light is not of one kind, but consists of a variety of kinds differing from one another by the colour with which they impress the eye, and by their refrangibility or capability of being bent round in passing through a prism, the red rays being bent round the least, and the violet rays the most, while there are kinds of light of all shades of refrangibility between the two extremes. If I were to form a coloured image or spectrum in this simple way it would not be what is called a pure spectrum. Suppose, for simplicity of explanation, we had only two kinds of light, blue and red, differing from one another in refrangibility, then the incident light would be decomposed into those two beams which would each diverge separately from the source of light, or rather from the virtual images of that source, and would be bent round to a very different extent in passing through the prism; consequently if we received them on a screen we should get two circular patches of light, one blue and one red. Now actually, as I have said, you have all intermediate shades of refrangibility, and therefore this compound fan-shaped beam, which passes through the prism, must be regarded as made up of a vast number of cones of light differing from each other in refrangibility, which increases from the red end to the blue end. Consequently if you were to receive the whole on a screen, any one point of the screen would not be illuminated solely by one kind of light, but by all the kinds the refrangibility of which lay within certain limits; in fact there would be a spectrum made up in this way, each circle that we draw representing the section of one of those cones, and each overlapping the neighbouring circles. How then shall we arrange to procure a pure spectrum, and that without loss of light? I say without loss of light, because a very simple mode, in theory, of obtaining a pure spectrum would be to limit a beam of light by one hole, and then by another at a distance; the diverging beam, which passes through the first hole, would be limited by the second, so as to transmit only a very narrow pencil of light, which you might regard as a mere ray, and if you allowed that to fall upon a prism, it would be bent round differently for the different kinds of light of which it consists, so that you would get in that way a pure spectrum, but at an enormous sacrifice of light. How then are we to obtain such a pure spectrum without loss of light? This diagram represents (Fig. A) a beam of sunlight diverging through a small hole, forming a pencil of light. If that were received on a convex lens at a sufficient distance (Fig. B), it would be brought to a focus again on the other side, and would diverge from that focus afterwards. If we were to take a prism alone, place the prism at a distance from the hole, and in its position of minimum deviation (Fig. C) we should get, if there were two kinds of light only, blue and red, two beams emerging in different directions, the blue (represented in the figure by interrupted lines) being bent round more than the red, and diverging as if they came from two separate points. Now suppose we combine these two pieces of apparatus

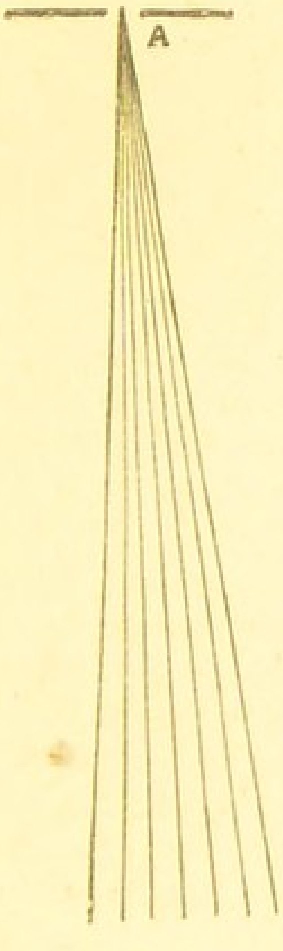

Fig. A.

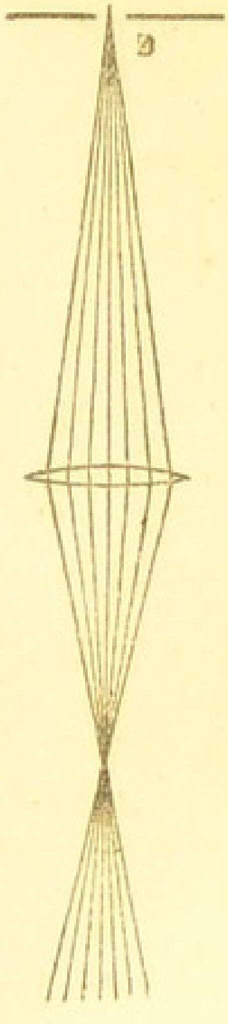

Fig. B.

together, placing the prism at a distance from the hole, and the lens near the prism (Fig. D). Then the prism and the lens each fulfils its own office, the prism causes each conical beam of light to be bent round, but differently, according to the nature of the light, more for the blue than the red ; the lens alone collects each of these conical beams, and brings it again to a focus, and so this figure represents what will take place.

If a screen were placed exactly in the focus, and white light containing light of all shades of refrangibility were allowed to fall on the prism, each point of the screen which was illuminated at all would be illuminated by one kind of light only; the different kinds would be separated from one another on the screen, and consequently you would get a pure spectrum, and that without the tremendous loss of light encountered if you employ two holes placed at a distance

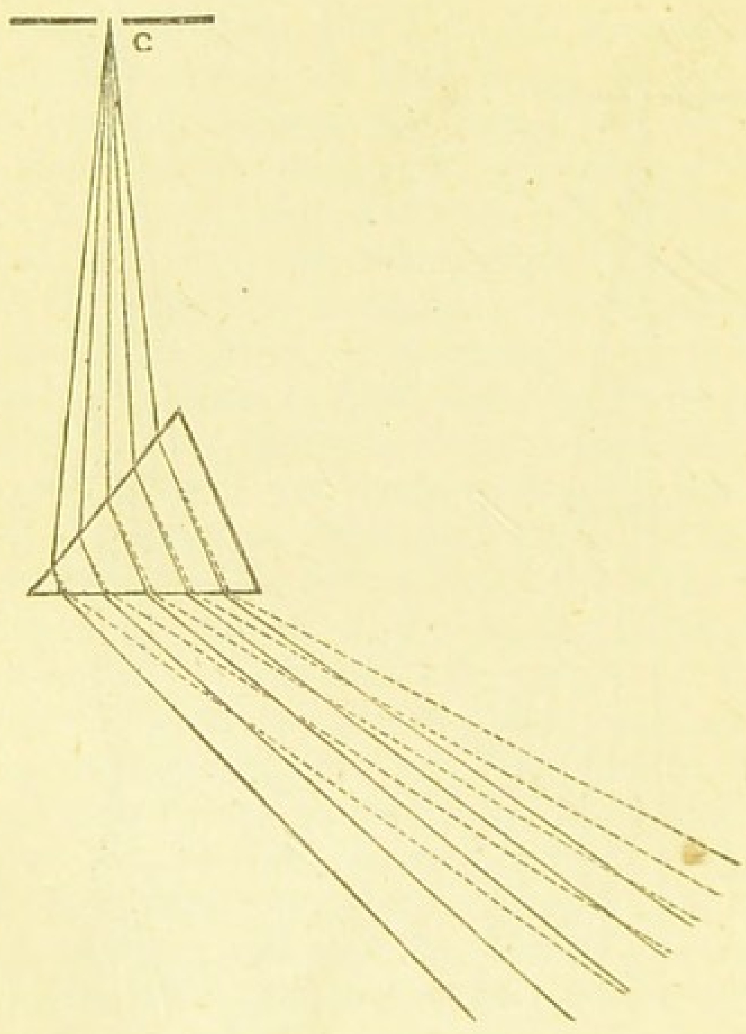

FIG. C.

from each other. The spectrum thus formed, though pure, would be infinitely narrow; but in order to give it breadth you have only to substitute a line of light (in a direction parallel to the edge of the prism) from the point of light; in other words, to transmit the light in the first instance through a narrow slit instead of a small hole. This is the way in which a pure spectrum is generally formed as a matter of principle, though sometimes a mirror is used instead of a lens;

but I will not go further into that, because what I have said is merely an introduction to the use of the prism in the simplest manner possible.

The simplest way to form a pure spectrum experimentally, and a way which suffices, provided you do not want to put objects in the spectrum, but only to see it, is to suppose the

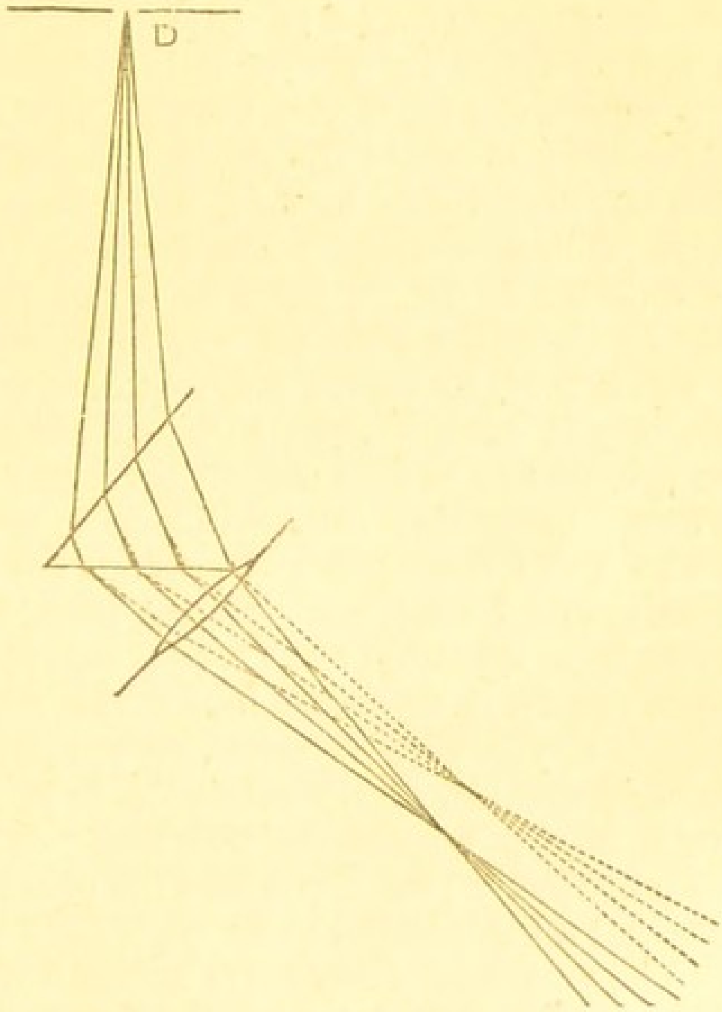

FIG D.

lens to represent your eye, and the screen placed in the focus of the lens to represent the retina.

I said that if the light was passed through a hole it would be brought to a point; but if it came in through a slit, which you may regard as a succession of holes in a direction perpendicular to the plane of the paper, then after passing through the lens it would be brought to a line of light standing out in a direction perpendicular to the plane of the paper, which is supposed to be the plane of refraction for light from the middle of the hole, a line of blue light for the blue light, a line of red light for the red light, &c., in different positions, so that the spectrum on the screen would be made up of a series of lines, red, yellow, and blue, &c., if there were so many different kinds of light. Every pure spectrum from a source of light allowed to fall through a slit is to be thought of as made up of a number, generally an infinite number, of images of the slit, corresponding each to the light of one definite refrangibility. Instead of having distinct images of the slit, as you would if there were only a definite number of degrees of refrangibility, if you have all shades you must regard the spectrum as made up of an infinite number of images of the slit placed side by side, and running one into the other with no line of demarcation between them, except in certain conditions in which there is a failure of certain kinds of light. Now the simplest way of seeing this is to take a slit, which may be of the roughest description, and a prism which is just large enough to cover comfortably the pupil of the eye, and to look at the slit through the prism as I am doing now. I now see a coloured image or spectrum, and in it the fixed lines of Fraunhofer. I presume you have heard of these already, and I shall not describe them, as it would take me too far from my subject. There is one point which I must notice in the use of the prism held in this manner before the naked eye. If you turn it round its axis, you will find that for a certain azimuth of the prism the fixed lines of the spectrum, or at least of a particular part that you are looking at, will be seen distinctly; but if you turn the prism a little this way or that round a line parallel to its edge, they will become indistinct. The particular direction or azimuth in which the prism must be held is found by trial. You can focus the spectrum by turning the prism one way or the other, until the image you are looking at is sharp and clear; just as in ordinary cases of focusing. The reason of that is easily explained by geometrical optics, or the science which treats of the mathematical consequences of the laws of reflection and refraction of rays of light. It depends on the alteration of the distance of the virtual focus from which the rays after refraction through the prism come according to the azimuth of the prism. I say virtual focus, although in point of fact, after passing in that manner through a prism, unless it be in the position of minimum deviation, the light diverges, not from a focus, but from two focal lines, as they are called. Now if you combine the prism with a lens in order to project the image on a screen, and allow homogeneous light to pass through a hole at a sufficient distance, and to fall on the prism when not in the position of minimum deviation, you will find in one position of the screen a vertical line of light, and in another position a horizontal line, and between the two you will get a circular patch. Now suppose that the screen is held in such a position that on it is formed the vertical line, how is the image of a slit which you substitute for the hole formed? It is formed by a succession of lines overlapping one another in the direction of their length, which gives you in fact a single straight line; so that when white light is used light of any one kind will be brought to a line on the screen, or in this case on the retina of the eye, and the spectrum will be seen distinctly. The particular azimuth in which the prism must be held to see the spectrum distinctly depends on the distance at which the slit is held from the observer, and on the length of sight of the observer, and it will be different from one end of the spectrum to the other. If I hold a prism so as to see the red end distinctly, I must turn it a little to see the violet end distinctly. Turning it in one way brings the virtual image nearer to the eye, and turning it the other way moves the image further off. If it is focused for the red by holding the prism in a certain position, we must turn it a little so as to diminish the angle of incidence, in order to get the true focus for the violet. The reason for that is, that there is no provision for chromatic compensation in the eye. The eye in that respect is to be compared, not to an achromatic object-glass, but to a simple lens. The effect of the dispersion of light as regards ordinary vision is not perceived under ordinary circumstances, but it becomes very perceptible indeed when you supply the eye with homogeneous light of different kinds, or with light from which certain portions are abstracted. I have tried the experiment of throwing a pure spectrum on a printed page. On holding the page at the usual distance of distinct vision, I was able to see quite distinctly in the green and brighter part of the spectrum; in the red end I saw somewhat indistinctly from long-sightedness; and in the violet end very indistinctly from short-sightedness.

In choosing a prism it is very easy to see whether the glass of which it is composed is good or not. If you look at the prismatic image of a candle, and then, keeping that in the field, move off the prism to arm's length, so as to get distinct vision of the prism itself, by moving it about a little you will be able to see whether it is free from veins or not. It should be free from veins, although a prism for merely eye-work need not be of the same excellence as if it were to be used with a telescope.

The more immediate object of my lecture is the coloration of natural objects, and that is best studied in the first instance in the case of clear coloured bodies such as solutions, or coloured glasses. Here is a coloured solution, and if I reflect the skylight through it you will see the colour is blue; but if I add a little more colouring matter to it, it is no longer blue but red. The same effect exactly would be produced if, instead of increasing the quantity of coloured fluid which was mixed with the water, I had increased the thickness of the stratum through which you looked—in fact one is found by experiment to have exactly the same effect as the other. What is the colour of this fluid? If you saw it only in one stage you would say it was blue, and if only in another you would say it was red. It passes in fact from blue to red. What is the cause of that? You must remember that this fluid is illuminated by white light, and white light is not all of the same kind, but is a mixture of portions of light, differing from one another by their refrangibility, and at the same time differing from one another in the coloured impression which they produce upon the eye. In glasses the colouring effect upon the eye simply results from the super-position of various kinds of light which are present. In order to study this phenomenon and the cause of it, we must in the first instance consider what would take place as regards one kind of light alone. If I had one kind of light (and approximately I should get that by a Bunsen flame with a bead of common salt introduced into it), supposing I viewed this through a wedge-shaped vessel which I can slide in front of my eye, if I begin where the thickness is nothing, no effect is produced. In this particular fluid, if I had such a flame before me, I should see at first no effect, and then, as I slid the vessel so as to increase the thickness of fluid looked through, the flame would become weaker and weaker, until I should not be able to see it. The effect is one of a progressive weakening. The longer the path of the light within this coloured or absorbing medium, the less the quantity of light which escapes; and the law according to which the intensity decreases is very readily obtained by a simple consideration. Suppose first we had a stratum of the fluid of a certain thickness, say one-tenth of an inch, and this produced a certain weakening in the light, or let through a certain percentage. Now if you treated the light which came through to a second stratum, also one-tenth of an inch in thickness, of the same fluid, it would let through the same percentage as before, and so on. When you have to deal with a mass of fluid you may in imagination divide it into strata each of the same thickness. Suppose here is the horizontal surface of a mass of coloured fluid, which we are observing in a vertical direction with white light. The effect of the fluid on light of any particular kind is simply to weaken it. If we divide the fluid into strata of equal thickness, in passing through the first the light is weakened in a certain proportion, depending on the thickness of the stratum. In passing through the second stratum the same percentage of the light will be let through, and so on; so that in passing from stratum to stratum the intensity of the light goes on decreasing in geometric proportion. That is to say, each term of the series expressing the residue bears to the preceding term of the series the same ratio throughout. Consequently when you get far enough into the stratum the light has been so much weakened that it becomes altogether invisible. Theoretically, however great the stratum, there is a quantity which still gets through, but practically, after a certain time, the quantity which gets through is so very small that it may be regarded as nothing at all, and the light is extinguished. Now the rate at which the light is so extinguished depends upon the kind of light which falls upon the coloured stratum. Suppose that rate to be different for different kinds of light, then if there were only two kinds presented to the fluid in the first instance, as it passed on and on, through this absorbing medium, the proportion of these two kinds of light would be continually changing. For the sake of clearness I will suppose there are two kinds of light to start with, blue and red, and that at the beginning blue has an intensity of 100 and the red of 10. There is of course a great predominance of blue over red. Now suppose in passing through a stratum of a certain thickness half the blue light is lost, and only half transmitted, and that ninety per cent. of the red light is transmitted. Then after passing through the first stratum the intensities will be respectively 50 and 9; after passing the second stratum of the same thickness the intensities will be 25 and 8·1; after the third 12·5 and 7·3; after the fourth 6·2 and 6·6, or about equal; but after passing through the next stratum they will be 3·1 and 5·8; so that although the quantity of red light was so much smaller to begin with, the red is more lasting, and in light which has passed through five of these strata the red now predominates over the blue. Passing through another stratum, the intensity of the blue is reduced to 1·5, whilst the red is 5·2, and so on; so that you see both kinds of light are weakened, but the proportion to one another is continually changing. That is a general explanation of what takes place in a fluid such as this [exhibiting an alkaline solution of archil]. I may mention that in almost all coloured fluids there is a continual change in the colour according to the thickness of the stratum of liquid, or, which will come to the same thing, according to the strength of the solution. For the sake of simplicity of explanation, I supposed there were only two kinds of light to deal with, which I called red and blue, but in point of fact when the fluid has white light thrown upon it we have an infinite number of kinds of light, and all shades of refrangibility, and each shade of refrangibility must be considered by itself. If we take a certain stratum of a coloured liquid or glass, or whatever it is, then after passing through that stratum the light will be weakened in a proportion which changes continuously in passing from one end of the spectrum to the other. The mode in which the total light passing through the stratum is made up may very conveniently be represented to the eye by a construction given by Sir John Herschel in his treatise on light. Suppose you take a horizontal line and lay distances along that line, or abscissæ, representing the places of the kinds of light which you have under consideration in some standard spectrum, and let lines drawn vertically, or ordinates, represent the intensity of the particular kind of light. If you care merely to know how the quantities go on changing as the light passes deeper and deeper into the absorbing fluid or glass, it will be simplest to take the original intensity as unity throughout, although we know very well that the different parts of the spectrum are not equally bright. But that is a point which we need not for the moment take into consideration. A horizontal line, then, parallel to the axis of abscissæ, may be supposed to represent for each particular colour, the place of which is defined by the abscissa, the original intensity of that colour. Now after passing through a certain stratum of the medium of a certain thickness, that intensity will be reduced differently for the different colours, and consequently the locus which defines to the eye the composition of the light which is passed through that stratum will be a certain curve, but it will depend on the nature of the medium what the nature of the curve will be. Now I have drawn here [referring to figure] what represents a curve for a green colour in a certain medium. To find how the light will be composed after passing through a second stratum of equal thickness, we have nothing to do but for a sufficient number of abscissæ to take an ordinate which bears to the ordinate of this curve the same ratio that the latter bears to the original ordinate or unity, and so on for additional strata of the same thickness. Thus we get a succession of curves representing to the eye the composition of the light which has passed through successive thicknesses of the medium. You may notice that the quantity of light altogether goes on decreasing; but that is not all, the proportion of the different parts goes on changing as well. In this case, if the opacity of the medium is such as is represented in this curve, the blue or bluish-green light which predominated a little at first will predominate more and more, and the colour of the medium will become a purer and purer green as you look through greater and greater thicknesses of it. Here is another curious curve representing in the same manner the type of light which is transmitted through one of the ordinary blue glasses coloured by oxide of cobalt. I do not pretend that it is an exact representation, but it is an approximate one, and you will see the curious alternations which there are in this case, of comparative opacity and transparency. In this way we can readily understand how it is that the colour of a coloured fluid is continually changing according to the thickness looked through. This phenomenon in its more striking examples is sometimes called dichroism, but as that word has been employed to designate so many phenomena totally different from one another in their mode of production, I hardly like to employ it.

You have seen in what manner you can readily, and almost without any apparatus, observe a pure spectrum, and how it is modified by the interposition of a coloured body; and I may just mention one or two instances of interesting results which may be obtained in this manner. Sometimes the mode in which a coloured medium attacks the different parts of the spectrum is highly characteristic of the particular fluid that you are employing. Here, for example, is one very characteristic case—the red colouring matter of blood. The spectrum which that gives is represented in the upper part of this figure [referred to]. In order to see the spectrum nothing more is requisite than this: You take a slit of the roughest description—here is one made of wood and tinned iron blackened, and the blood is conveniently held in a test-tube, which you can hold in position by an elastic band. In order to see the spectrum by transmission you have nothing more to do than to hold this against a source of light and look at it. If you use, not a wedge-shaped vessel, but a test-tube, you cannot be sure of not passing over some of the most interesting parts of the phenomena, unless you go step by step, and use several different thicknesses, or, which comes to the same thing, different degrees of dilution. For instance, when a solution of blood is so highly coloured as this, a great part of the spectrum is cut off, and it may be that you will see nothing but a broad black band, whereas, if I had used a weaker solution or a test-tube of smaller diameter, I should have seen certain highly characteristic phenomena of absorption. In order to see these, the solution must be so diluted that it is little more than pink. Then you will see these highly characteristic dark bands of absorption. I know of no substance which can be confounded with blood if you simply take the spectrum of it in this manner, unless possibly an out-of-the-way substance, turacine, the colouring matter found in the red feathers of the wings of the touraco, a bird found at the Cape of Good Hope. If you only looked at the spectrum in one condition, it is possible that the two might be confounded, although hardly so; but if you combine the observation of one of these peculiar spectra with the observation of the effect of re-agents, you get a combination of characters which is such that it is almost impossible to confound any other substance with the one which you have under your hands. This becomes a mode of discrimination between substances of the utmost value to chemists, but which, strangely, for a long time they altogether neglected, though, since the researches of Kirchhoff and Bunsen, the chemical spectroscope has become an instrument in the hands of almost every chemist.

I may mention one reaction with reference to the colouring matter of blood which is interesting in itself, and will also illustrate what I am saying. You know that the venous and arterial blood differ from each other in colour. If you look at the veins at the wrist you can see the redness of the arterial blood in the arteries which happen to be near enough to the surface, as contrasted with the deeper and darker colour of the venous blood. This difference can be imitated by introducing into a solution of blood a suitable deoxidising agent, which will alter its colour. I have here, in the first instance a solution of protosulphate of iron, and I have added to that tartaric acid, which has the property of preventing the precipitation of many metallic oxides. The colouring matter of blood is immediately decomposed by acid, and therefore you must take care not to introduce acid into the solution. I have rendered this solution alkaline by ammonia without precipitating the iron. This is a strong reducing agent. It is in small quantity almost colourless, and if a little of that is introduced into the colouring matter of blood, which is not decomposed in any reasonable time by ammonia, then immediately the colour is changed into a purple one, and the spectrum is changed in a remarkable manner, as represented in the lower half of the diagram. In lieu of the two dark bands, you have a single band occupying an intermediate position. The fluid is purpler than before, and lets through more blue light. If you have such a solution in a test-tube, and shake it up with air so as to re-oxidise it, you get back the original solution, and you may put it backwards and forwards as often as you like. But I merely mention this as illustrating what you get by using simply a prism without any apparatus at all, and you can see the actual spectrum as shown on the diagram. If a test-tube containing a solution of blood deoxidised in this manner be allowed to stand for some time, it absorbs oxygen from the air, the upper part becomes oxidised, and this oxidation extends deeper and deeper down, and after a certain time the upper portion of the blood is seen of the scarlet colour, and the under portion of the purple colour. If you then put the test-tube behind a slit, such as I have shown you, and look at it through a prism, you will see the two spectra simultaneously, as represented in the figure.

To take another example, I have here a solution of permanganate of potash. If it is considerably diluted, and you analyse the light transmitted through, you will see a broad dark band in the spectrum. If you have it more diluted, you obtain a spectrum highly characteristic, in which are seen five dark bands in the green part of the spectrum. Those are highly characteristic of the permanganates. There is just a trace of a sixth band, which comes in when the solution is stronger. These are alternations of transparency and opacity, not that the fluid is perfectly transparent, but these intervening spaces are really alternations of greater and less absorption. When the quantity present is sufficient, the whole of this region is absorbed, and then the characteristics are lost, because there are a great variety of purple substances which would give a spectrum not very different. In examining a substance you must dilute the solution to make sure of breaking up any such broad dark region, and then you see the dark bands, if any, which are characteristic of the substance. There are other red solutions of manganese which may be obtained, and which agree with the permanganates in being powerfully oxidising agents, and which long ago were confounded by chemists with the permanganates because they have both the purple colour, and are powerfully oxidising agents. For example, if you rub up binoxide of manganese with binoxalate of potash, you obtain one of these purple coloured solutions, though it is not very permanent, which as being a powerful oxidising agent and also of a purple colour, was supposed to contain permanganic acid, but the spectrum instantly shows you it is nothing of the kind. These two examples will suffice to show how valuable the prism is, even without any other apparatus, as a means of discriminating between different bodies.

The phenomena of the coloration of natural bodies is best studied, as I said before, in coloured solutions; but I now pass on from that to the colours of natural bodies as commonly presented to us. Let us take, for example, a very common colour, the green of vegetation, as in grass and leaves in general. What is the cause why a green leaf is green, or why a red poppy is red? It is frequently said that the reason why a red poppy is red and that a white lily is white is, that the lily reflects rays of all kinds, but the poppy reflects only the red ones, and if you place the red poppy in a pure spectrum it is luminous, like a white lily, in the red; but if you place it in the green it will be almost black, whereas the white lily will be brilliantly green. Now the common explanation, properly understood, is true; but it is not the whole truth, and if understood as it is liable to be understood, it is false. It is true that a red poppy reflects red rays, and a white lily reflects rays of all colours; but it is not true that the preference for the red to the green in the one case and the equality of action in the other takes place *in the act of reflection*. It is not a phenomenon of coloration by reflection. The coloured light is reflected, or you would not see it; it is sent out of its course before it enters your eye, and it is true that the light, in its life's history, undergoes reflection; it is not true that it is in the act of reflection that the one colour gets the preference over the other. Here I have some solution of the colouring matter of green leaves in alcohol, and here is some more alcohol, with which I will dilute the former. I have obtained a beautiful green solution, although the green colour is not seen now by reflected, but by transmitted light. As regards the light which falls upon the surface, there is a little white light reflected, just as there would be from water, but very little is reflected from the surface where the fluid is in contact with the glass; the chief portion of that reflected being from the outer surface of the glass itself. You would not see any green at all in it unless there were something placed behind so as to reflect the light backwards. You see there that the colour of the green leaf, as ordinarily seen, is due to the combination of reflection with the phenomena of absorption, or the swallowing up of certain kinds of light when light is sent through a perfectly clear medium. I may illustrate this in another manner. Here is a vessel of water, into which I will pour some blue solution. If I send light through it, it will appear of a deep blue, but if I hinder the light from coming behind, which I can do by putting black cloth behind it, it is simply dark; you do not see the blue colour at all.

Why? Because there is nothing behind to reflect the light. Suppose I make it a little muddy by pouring into it some pounded chalk, you see the blue colour immediately. Why is that? You know that if powdered chalk were put into water it would not colour the fluid. But here each little particle of uncoloured chalk reflects a small quantity of light falling upon it, so that it fulfils the same office as a mirror placed behind the fluid. You may imagine that the particles of chalk are so many minute mirrors capable of reflecting light. If you take any one particle of chalk, say one-tenth of an inch deep, in the liquid, the light from the sky falls upon the fluid, it undergoes absorption in passing through that first tenth of an inch, and then the portion of light which is left is reflected by that little particle of chalk, and passes out again, and so, as regards that single particle, the light which reaches your eye from beneath that depth has itself gone through a stratum of fluid of one-fifth of an inch in thickness, and accordingly you see the colours produced by selective absorption, that is to say, by the absorption of certain kinds of light, which are more greedily devoured by the fluid than the other kinds. This is what takes place in the green leaf, and in the petals of flowers. Let us take the white lily. If the petal of the flower had been merely a sheet of thin glass, you would not have seen that white colour. There would have been a little light reflected from the first surface and the back surface, but the petal is really composed of a vast assemblage of little cells, at each of which partial reflection takes place, so that it resembles some finely-powdered glass, which would form a white powder, because each little surface is capable of reflecting the light, although a single sheet of glass would not be white. The petal of the white lily is just in the condition of the powder. It is full of little cells, full, optically speaking, of irregularities, from each of which a portion of light is reflected, so that, all kinds being reflected alike, and there being nothing in the white lily to cause preferential selection of one over the other—nothing to sift the light, as it were—you get a considerable quantity of light reflected back to the eye, but it is white. What is the difference between that and the red poppy? The red poppy is, as it were, a white lily infused with a red fluid; there is light continually reflected backwards and forwards, just as before, at the surface of the cells; but that light, in going and coming, passes through the coloured juice of the plant. It is the same thing with a green leaf. The structure is irregular, optically considered ; there are constantly reflections, backwards and forwards, of light, which penetrates a little depth and is reflected, and has to pass through a certain stratum of this colouring matter, to which the name chlorophyll has been given, but which is really a mixture. That is what takes place generally as regards the coloration of bodies; it is a phenomenon not of reflection, not of selection of one kind of light for more copious reflection than another, but of absorption, or the swallowing up of certain kinds of light. Reflection comes in, in order to enable us to see the light which otherwise would not enter the eye at all, but would go off in another direction.

The spectrum of this green fluid, which is a substance to which I have paid a great deal of attention, is very peculiar. It is a mixture of several substances with closely-allied chemical properties. The peculiar spectrum may be seen in a green leaf itself, if you place it behind a slit and analyse it by transmitted light, or allow a strong light, such as that of the sun, to fall upon it and analyse the reflected light.

Now you will say, Are there no colours in any case produced by reflection? is there no case in which this preferential selection is made? How is it, for instance, if you take a plate of gold; that reflects light regularly, but the light is coloured yellow? I said the cause of the coloration of bodies in the great bulk of cases was what I have just described, but I did not say that was the sole cause of coloration. The light reflected from gold is in fact coloured ; in the case of gold or of copper there *is* a preferential selection in the act of reflection of one kind of light rather than another, and that preferential selection is not confined to the metals, although it is chiefly in gold and copper that we ordinarily perceive it. There are many cases in which substances which absorb light with intense avidity present a similar reflection of coloured light, and in these substances the connection between the intense opacity of the substance and the coloured reflection can be better studied than in the case of metals, because a metal is, under ordinary circumstances, opaque. Certain of the aniline colours, for instance, show the coloured reflection in a notable manner. These specimens on the table (referring to plates of glass on which solutions of certain aniline colouring matters had been evaporated) were given to me by the late

Sir Charles Wheatstone. He prepared them himself. This is a deep blue or purple by transmitted light, but it is an exceedingly thin film, and by reflected light it has a bronzy appearance. Here is another which is green by reflected light and red by transmitted light. In these cases we see that we have a substance which does exercise a preferential selection for one kind of light as compared with another in the act of reflection. But the light which is so selected for preferential reflection is not at all the light which is chiefly transmitted; on the contrary, it is the very reverse. If we analyse the light transmitted through this red stratum, or through a solution, we shall find that in the green part of the spectrum the substance is more intensely opaque than elsewhere; that is to say, the film must be excessively thin, or the solution excessively dilute, in order that any light at all strong enough to be seen may get through in the green part of the spectrum. The substance is intensely opaque as regards the green, but moderately opaque only as regards the other parts. A solution of this colouring matter does not present this coloured reflection at all. The colouring matter must be excessively concentrated, as it is when a solution of it is dried on glass, in order that this reflection should be shown, and then the kind of light which is more especially reflected in that manner agrees with the kind of light which is intensely absorbed. Those parts of the spectrum which are absorbed with this enormous intensity, so that the dry film is with regard to them as opaque as a film of metal of the same thickness would be, or thereabouts, are reflected as copiously as they would be by a metal, and the colours which are only moderately absorbed are reflected very much as they would be by the glass, and accordingly in the reflected light there is a predominance of those colours which are intensely absorbed. The most remarkable example, that I know of, of the connection between intense absorption and powerful reflection, takes place in the case of crystals of permanganate of potash. These crystals have a bronzy look by reflected light when freshly taken out of the mother liquor, so that the surface is not spoilt by tarnishing, as soon happens from exposure to the atmosphere; the sides of the crystals have a metallic brilliancy, and reflect green light. Now that light agrees with the light reflected from a metal, not only in its copiousness, but also in certain other properties. If I take light reflected from glass at a certain angle, which is called the angle of polarisation, the reflected light is polarised, and capable of being extinguished by an analyser such as a Nicol's prism. Light reflected from a metal is not polarised at any angle of incidence, though it is partially polarised at an oblique angle. I say partially polarised, but I will leave the explanation of that to my friend Mr. Spottiswoode, who will give a lecture on that subject. Bronzy crystals of permanganate of potash agree in that respect, to a certain extent at least, with the metals; if you examine the light by reflection you find that it is not capable of extinction by analysing under any conditions. If you examine it at such an angle of incidence that a vitreous substance would give you light capable of extinction, the light becomes weaker and of purer green. I have analysed the light reflected by a crystal under these conditions, by a combination of a prism and a Nicol's prism, so as to extinguish what light would have been reflected from glass under similar conditions, and this curious result came out. I must premise that crystals of permanganate of potash are too intensely opaque to allow you to examine them by transmission, but you can make a solution of them and examine that, and it shows these bands of absorption which are shown on the diagram [referred to]. Now on examining, in the manner I have mentioned, the green light reflected from the crystals at an angle similar to that at which light reflected from glass would have been quenched by a Nicol's prism, this curious result was obtained; the spectrum was seen to consist of four bright bands, and perhaps a trace of another, the rest of the spectrum being wanting. Now what were the positions of those four bands? When the positions were observed, by referring them to the standard fixed lines of the spectrum, which were seen at the same time, they were in the positions represented in the under part of that figure; they agreed in position with the first four of the five dark bands seen in the transmitted light. The spectrum begins to get comparatively faint in the region of the fifth band of absorption, and there was hardly a chance of seeing the fifth bright band if it had been there; but you see that whereas, as regards transmitted light, the crystals pass alternately through maxima and minima of transparency—alternately from the condition of a vitreous substance to the condition of a metal, as to the avidity with which they absorb the light—corresponding to these alternations you have also alternations in the character of reflected light; so that you may say the substance is alternately opaque and transparent, comparatively speaking only, as regards the transmitted light, and, corresponding to these alternations, it behaves as regards reflection alternately as a metal and as a vitreous substance. That shows how the coloured reflection, where it does exist—it is a phenomenon, comparatively speaking, rare—is connected with the quasi-metallic opacity of the substance as regards transmission.

You may say that if that be the case the colour of gold ought to be not yellow at all by transmission; nor is it. Gold leaf is thin enough to allow some light to pass through it otherwise than by mere holes, which occur accidentally here and there, and that transmitted light is green. I have here a little chloride of gold in solution. I put a little protosulphate of iron in it, and if the experiment is properly performed you obtain what is not really a solution of gold, but gold suspended in a state of exceedingly fine division; and in that way, when the fluid is looked through, you get it distinctly blue, which is the real transmission colour of gold. I have seen the same thing with regard to copper. Dr. Percy gave me a specimen of a very curious glass, which I intended to have brought with me. The ordinary red glasses are coloured by suboxide of copper, which is put over a piece of colourless glass in a film of copper-salt so thin that you do not see any colour at all by light transmitted directly across, but where you look through obliquely you can just see the faintest possible blueness. The film of copper-salt is reduced by a suitable agent to a silicate of suboxide, which gives that beautiful red colour, which is contained in a film thinner than the thinnest paper. In this case the glass was covered with copper in a similar manner, but it was a deep blue by transmitted light, and if you play on any particular spot with a blow-pipe it becomes sensibly colourless. The colouring matter was copper, but in what state? Evidently in this case the reduction necessary for reducing the oxide of copper to suboxide had gone on rather too far, the copper was reduced to the metallic state; you looked *through* the copper, and it was seen to be blue. So that you see that in the same sense in which the coat of an English soldier is red, the colour of gold is blue or green, and the colour of copper is blue. There is the same relation there as in this aniline glass between reflection and absorption, but whereas in the aniline colours it is commonly the phenomena due to absorption, and the selection of one kind of light over another in the act of transmission, which meet your eye, in the case of the metals gold and copper it is a selection which takes place in the act of reflection which ordinarily presents itself to observation, and the true colour by transmission is only seen under very exceptional circumstances.

FLUORESCENCE.

BY PROFESSOR STOKES.

THE subject which I am about to bring before you to-day is one which has attracted a great deal of attention for some years back, and in which I have myself had a considerable share. One of the first phenomena discovered in connection with those I have to bring before you was that which Sir David Brewster called the internal dispersion of light, which he first noticed in an alcoholic solution of the green colouring matter of leaves, as mentioned in a paper read before the Royal Society of Edinburgh in 1833,[1] and fully described in a later paper read before the same Society in 1846.[2] I have here a solution of the green colouring matter of leaves which I used in my lecture on absorption, but which I am now going to use for a different purpose. Brewster had occasion to pass a beam of sunlight through this green fluid, and he was surprised to observe the whole of the path of the beam exhibiting a blood-red light. The figure which I have here[3] is intended to represent what could be seen, and I will endeavour to show it presently. This represents a vessel filled with the green fluid and placed on a white ground such as paper, with a glass bottom so that you can see the light through. In looking through you see the green colour of the solution, and there is supposed to be a board standing vertically on its edge containing a lens. The sun's light is reflected horizontally and sent through that lens so as to form a condensed beam, the focus of which lies within the

[1] *Edinburgh Transactions*, xii. 541.

[2] Ibid. xvi. 111 ; or *Phil. Mag.* for June, 1848.

[3] The figures referred to in this lecture are not reproduced, except in two cases, as they are mostly coloured, and would lose much of their significance if merely represented by black and white.

vessel. When that is done, you see the whole path of the beam marked by this blood-red light. This is a very curious phenomenon: what is the cause of it? Sir David Brewster seemed to imagine that the ultimate particles of the substance reflected red light somewhat in the manner of finely suspended vermilion. Suppose in fact you had a fluid which was green by transmitted light, and you could manage to form in that an excessively fine mud of vermilion, then it is conceivable that you might get a phenomenon of this kind; I do not say that is the true cause, for it is not. Brewster examined a number of substances, both solutions and solid bodies, in a similar manner, and I may mention one which is described by him in a later paper read before the British Association in 1838, a certain variety of fluorspar. One of the varieties he mentions is a green kind as seen by transmitted light, found at Alston Moor in Cumberland, and I may mention that there is another variety, which usually is purplish by transmitted light, which abounds in Mr. Beaumont's lead mines at Allenhead, which shows the phenomenon even better. This kind of fluorspar shows a deep blue light in certain aspects. You see that to perfection, if you plunge the spar into water, because then you get rid in a great measure of the light reflected from the surface. When a condensed beam of sunlight is admitted into the crystal, the path of it is marked by a blue light. It is not, however, continuous, like the red light in the green fluid, but it occurs in strata parallel to the nearest faces of the cube. Evidently it depends upon something which took place during the growth of the crystal. Possibly it may have crystallized thousands of years ago, we know not how long, out of a solution, the nature of which gradually changed as the crystal grew, and some substance probably was taken up by the crystal, to which this effect is due.

Some years later Sir John Herschel published a paper in the *Philosophical Transactions*, "On a case of superficial colour in a colourless liquid," which was shortly afterwards followed by a paper "On the epipolic dispersion of light.[1]" Quinine as you know is very much used in medicine, and when a solution of quinine is formed, tolerably dilute, in water acidulated

[1] *Philosophical Transactions*, Jan. 1845, pp. 143, 147.

with sulphuric acid, by transmitted light the fluid looks very much like water, but it exhibits in certain aspects a blue colour. You will not perhaps very well see it here, but this is such a common fluid, easily obtained by anyone, that it is almost sufficient to mention the appearance. What is remarkable about this blue colour is that (unless the solution be excessively dilute) it is mainly concentrated, and occurs in an exceedingly narrow stratum adjacent to the surface by which the light enters the fluid. This diagram [referred to] represents the appearance.

This [referring to figure] is supposed to be a section of a tumbler containing the solution, placed on a black ground, and tolerably near a window from which light is coming in approximately horizontally. When you look down from above you see that the side of the fluid next the window is marked by this bluish colour, and when you hold the eye almost in a prolongation of the anterior surface of the fluid you see this blue stratum very much foreshortened and thereby increased in intensity, because the fluid itself is transparent like water, and the blue light which appears, whatever may be its cause, is seen perfectly well through it. When you look down in an oblique direction you see it much less intense. It is seen in perfection on allowing the light to shine from above, holding the eye a shade below the level of the upper surface, and putting a black object to make a dark background.

Now what is the nature of this blue light? Sir John Herschel tried various experiments on it. He analysed it by a prism, and obtained a continuous spectrum. He noticed, however, that he did not see the Fraunhofer lines in the spectrum; but whether they were really absent, or that he did not see them because the light was not strong enough, he does not seem quite decided. He noticed also that the blue light exhibited no trace of polarisation. He examined further the light transmitted through the solution to see what blue rays were taken out of it. Naturally he was led to scrutinise more particularly the blue part of the spectrum, but apparently the blue part of the spectrum was like the blue part of the spectrum of light which had come through simple water; there was nothing particular to be seen in it to account for the phenomenon. Possibly however, if this superficial colour is produced once only, the quantity of light removed from the spectrum may not be sufficient to show any dark bands of absorption in the blue region, but if you repeated the process on the light, making it pass through different vessels in succession giving out this blue stratum at the surface of each, perhaps then you would have sufficiently weakened the blue of the transmitted spectrum to show what particular rays were taken out by the fluid. Sir John Herschel however observed that when the light had passed through a thin stratum of the fluid in the first instance, though it resembled ordinary light when it came out, it had lost its power, for some reason or other, of producing this phenomenon. What the power was did not at the time further appear. Sir John Herschel called the phenomenon *epipolic dispersion* from a Greek word signifying surface, and he called the light which having passed through a moderate thickness of solution of quinine had been shorn of the power of producing that effect, *epipolized*. In one of his experiments he had occasion to throw sunlight vertically downwards on the fluid, and in that case, the light being pretty strong, he observed the blue colour extending to a depth of half an inch or more into the solution. It was much stronger at the surface, but extended a considerable way down.

After the appearance of Sir John Herschel's paper, Sir David Brewster took up the subject and examined this particular fluid, the solution of quinine, as he had done the solution of the green colouring matter of leaves and fluorspar, and various solutions,[1] and he found that when a beam of sunlight, concentrated by a lens, was admitted into a solution of the quinine in dilute sulphuric acid, the whole of the path of the beam was marked by this blue light. At the same time, if you repeat the experiment, you will see at once that the blue colour is decidedly more copious in the immediate neighbourhood of the first surface. He further examined the beam as to its polarisation, by viewing it through a rhomb of calcareous spar, and stated that a considerable portion of it, consisting chiefly of the less refrangible of its rays, was polarised in the plane of reflection, while the greater part, constituting an intensely blue beam, was found to be unpolarised. It is almost impossible to get

[1] See the paper already referred to, *Edinburgh Transactions*, xvi., or *Phil. Mag.* June 1848.

a fluid or solution like this perfectly free from motes, and the motes which are present will reflect a certain quantity of white light, and that light is principally polarised when looked down on vertically from above in a plane passing through the beam. When the beam is viewed by light polarised in the perpendicular plane, any light which would be reflected from motes is nearly got rid of, and the blue light is seen in its purity.

In this mode of observation it clearly appeared that the solution of quinine belonged to the class of bodies in which Sir David Brewster had discovered what he called internal dispersion. Among them there is a kind of glass which exhibits it in a very remarkable degree. Here is a specimen of the glass ; it is coloured by sesqui-oxide of uranium. He noticed in this case, that the whole of the beam was unpolarised, or, as he expressed it, possessed a *quaquaversus* polarisation.

It was twenty-five years ago last Easter, when I was preparing for my optical lectures in Cambridge, that, having had my attention directed by a friend to this solution, I procured some, and I was greatly struck with the remarkable appearance of the phenomenon, and the question occurred to me what was the cause of it. Now for my own part I had the fullest confidence in the doctrine that the light belonging to a given part of the spectrum is homogeneous, or all of the same kind. I am not now speaking of polarisation. It has been supposed by some, by Sir David Brewster, for instance, that the light of a given part of the spectrum, although no longer decomposed by the prism, might be decomposable by other means, for example by the use of absorbing media; and he thought he had obtained white light from a particular part of the spectrum by the use of a suitable absorbing medium. This has since been proved to be merely an illusion of contrast. Having, as I said, felt the fullest confidence in the principle that the light of a given part of the spectrum is homogeneous, I felt little doubt that if the principle were faithfully followed out, it would lead to a solution of the problem what the nature of the light which produced this effect was. At first I took for granted that the blue light, which the prism shows to be heterogeneous and not mere prismatic blue, a compound of various colours, a little red, more green, but with a predominance of blue, could only have come from light of the same refrangibility in the incident beam; but in following out the consequences of that, I was led of necessity into utter extravagances as regards the cause of the phenomena, extravagances which did not appear to have any resemblance to truth ; and on further reflection it occurred to me that perhaps after all this blue colour was not produced by the blue rays of the spectrum at all, but by other rays. We know that the spectrum contains rays which are invisible, but in all other respects behave exactly like light. But the invisibility is a mere accident, so to speak, depending on the organization of the human eye ; and the eyes of animals in general are probably very much like the human eye in this respect, although it is quite possible that certain animals may see rays which we do not ; but that we cannot well make out. We know that light contains besides the visible rays others which are invisible ; some less refrangible than the red, and others more refrangible than the violet. We know that the latter show themselves especially by their chemical effect, for example, on a properly prepared photographic plate, and abound in sunlight and daylight, which show strongly the blue light given out by quinine solutions, while lamp-light, which we know to be poor in those rays, shows it but feebly.

Then it occurred to me that perhaps this blue colour which the solution gives out is after all the work of the invisible rays which we know to accompany the visible ones. If we suppose this fluid, which looks colourless like water, to be excessively opaque, inky black as it were, with regard to the invisible rays of high refrangibility, and if we further suppose that these invisible rays are capable of so working on the fluid as to cause it to give out visible light, then the explanation of epipolic dispersion and the nature of epipolised light will be perfectly plain.

Now as we have been going on for some way without any experiment, I will have the room darkened, and will endeavour to show you one or two. I will take the original fluid in which the first phenomenon was discovered Here is this green solution of leaves, and you will be able to see a little of the red light. Here is the yellow glass I spoke of, and in this the green band will be seen very copiously ; here, again, is a solution of quinine, and with this I will endeavour to show you the fundamental experiment of Sir John Herschel, that this epipolic dispersion is a thing which cannot be repeated; once done the light is shorn of the power of producing it. I send a beam emanating from the electric lamp horizontally, and reflect it downwards on the surface by a mirror. There is a second vessel of the solution which I place floating in the other, and the blue stratum is seen at the upper surface of the fluid in the upper vessel, while the quinine in the lower vessel shows nothing of it. There is still the general diffused light, but this intense blue stratum is wanting altogether beneath the bottom of the upper vessel. Now I will replace the upper beaker by one of water, when you will see the difference. Just below the bottom of the upper vessel you have this intense blue stratum, whereas the light passing through the water in the upper beaker shows nothing of the kind. That is evidence that when the blue stratum is formed once, the light is shorn of the power of forming it again.

As the room is darkened I will show one or two more examples of highly fluorescent solutious before I proceed. Here is a solution obtained in a particular manner, which I will mention by and by, from the bark of the horse-chestnut.

I told you what occurred to me as to the cause of the phenomenon, and it was easy to test it. I will not go through all the experiments I tried, but pass at once to what you may regard as the fundamental experiment. Suppose we form a pure spectrum in the ordinary way; that we reflect the sunlight horizontally into a darkened room, passing it through a slit, and at a distance from the slit place one or more prisms combined with a lens, so as to form at the focus of the lens conjugate to the slit a pure spectrum. If you were to receive the pure spectrum on a screen, you would see the various colours, and if it were pure enough you would see the principal Fraunhofer lines. Now suppose instead of a screen you receive it on this colourless fluid. The appearance is rudely represented on this diagram.

I must mention that portions of the diagram are merely diagrammatic, namely, the top and bottom. The middle part represents what you actually see when you look down on the solution, but the top represents what you would see on a screen if you placed a screen there to receive the rays. This figure represents what is seen horizontally. The rays enter the solution of quinine, and the red, orange, green, and blue rays pass through it as through water, and come out on the other side, and if you received them on a screen, you would perceive the spectrum unmodified; but when you get to about the beginning of the violet, the path of the rays within the fluid is marked by a beautiful sky-blue light, which at first extends right across the vessel, and then the extent falls off as you get towards the end of the violet. But the light does not stop there. This

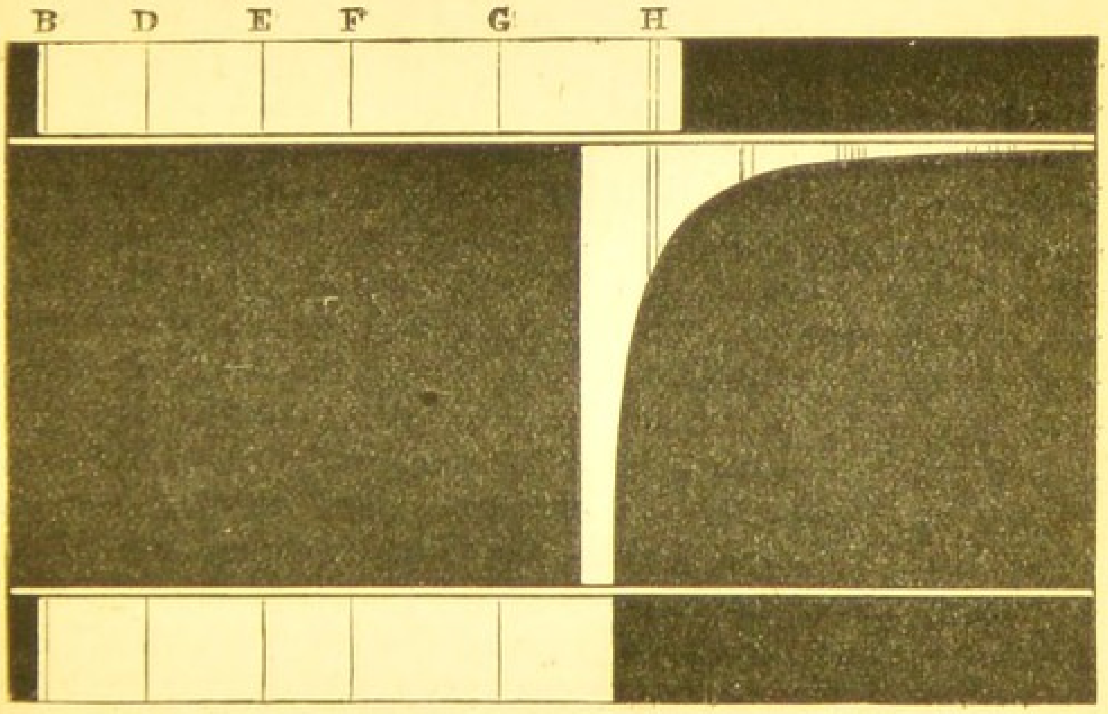

FIG. 1.

blue light extends far beyond the violet into a region of the spectrum which contains only invisible rays; and if the spectrum is pure you see not only light there, but interruptions which are of the same nature as the Fraunhofer lines which are seen in the visible spectrum. On a screen of paper placed vertically to receive the light, the Fraunhofer lines would be seen as distinct vertical lines when the paper was in focus, and would be seen a little imperfectly if the paper were a little out of focus. If you imagine the paper placed in one position, and moved towards or from the light, any particular dark line may be considered as having a *locus* in space, and that *locus* in space of one of the dark lines is what you may call a dark plane. At a considerable distance from the focus it would diverge out, forming a sort of wedge. These dark planes are seen as interruptions to the blue light. What are the Fraunhofer lines? They are parts of the spectrum when the light is missing, and consequently any effect the light is capable of producing will be missing too. Therefore when we get to the invisible region, if the invisible light is missing the visible light which that might be capable of producing will be missing too, and therefore you will see interruptions in this continuous mass of blue light. It constitutes a very striking experiment with sunlight, when you form an approximately pure spectrum by placing some prisms close to a pretty broad slit, and take a tube filled with the solution of quinine, or a prepared solution from horse-chestnut bark, and make it pass through the different parts of the spectrum in succession, beginning at the red end. At first it looks like water by transmitted light; the light rays are transmitted through it as they would be through water, on to the blue, but when we get on to the violet then the whole of the tube is lit up with this faint ghostly sort of blue light; when you have got beyond the visible rays altogether the tube is still lit up with the blue light. This shows that the explanation which occurred to me is really the true one, and that this blue colour is produced, not by the blue rays of the spectrum at all, but by other rays altogether; that rays of one refrangibility act on the fluid in such a manner as to cause it to give out rays of a different refrangibility altogether, or rather, of a different series of refrangibilities, because if you examine a small portion of this blue light, produced by rays of one definite refrangibility only, as you may do by putting the solution in a pure spectrum and placing a slit in front, so as to let only a narrow strip of the incident rays shine on the fluid, and then analysing the narrow beam from above by a prism applied to the eye, you will find that the light is not homogeneous at all. Nor again is there anything in the phenomenon which recalls to the mind the acoustic phenomenon of harmonics; the light is perfectly heterogeneous.

I have on one of these diagrams another mode exhibited of examining the refrangibility of the light which is emitted in this manner. This part is supposed to represent what would be seen if you place a screen to receive the incident rays, but which is not seen because you do not have a screen there. Take a small portion of the spectrum, and condense it further with a very small lens fixed in a blackened box, so as to get a very condensed beam. This is supposed to be a vessel containing one of these fluids, and the appearance you get is this, but so long as you are in the visible spectrum there is, generally speaking, an image of the double cone due to the light reflected from motes, which it is practically impossible to get rid of; that is followed at a certain interval by a beam extending over a greater or less width of the spectrum, and which is heterogeneous, that is

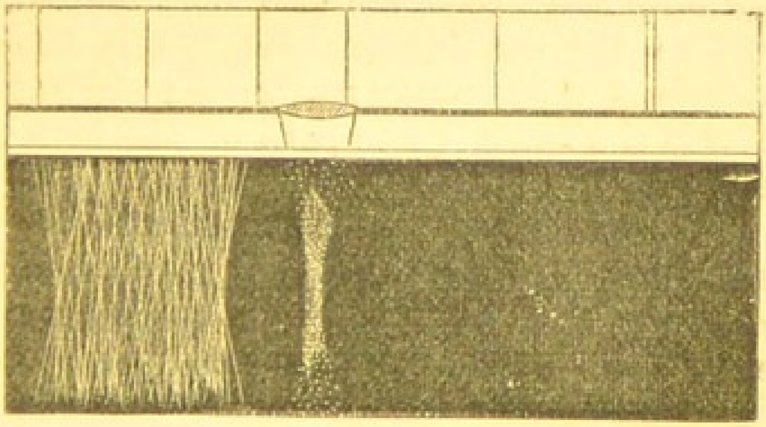

FIG 2.

to say contains lights of various degrees of refrangibility. And if you analyse the light by a Nicol's prism or double-image prism, you will see that this speckled image is almost wholly polarised in the plane of reflection, indicating that it is merely due to reflected light, whereas the other, in the case of a solution, is wholly unpolarised.

The phenomenon being thus explained, so far as to make out the immediate nature of it, it was to be expected that something of the same kind would be observed in other instances of what Sir David Brewster called internal dispersion, but I may mention that under that term he classed together two phenomena which in reality are utterly different as to their nature. In certain cases you get what is virtually a powder in fine suspension, so fine that it does not subside in any reasonable length of time, and gives you what looks like a pretty bright solution, but which really contains suspended matter. In such cases if you introduce a beam of condensed sunlight, the path of the beam is marked by light, because these motes reflect the light which falls upon them, but that light is reflected and is polarised by reflection, and this origin of the light is known by its polarisation. Moreover, being simply reflected it sends back the light which falls upon it unchanged in kind, whereas the truly dispersed light differs altogether in its nature from the light which falls upon the solution, glass, or crystal that shows it.

Now as I say the phenomenon being referred to the cause just explained in the one case, you may expect that in other cases something similar would be perceived, and I will take now the green solution obtained from leaves. I will suppose the experiment exactly the same, but the result is different in appearance although the nature of the phenomenon is the same. The path of the rays within the green fluid is marked by a blood-red light, which in different parts of the spectrum penetrates to a greater or less distance into the fluid. In this case the phenomenon begins very near the red end of the spectrum, somewhere about the line B of Fraunhofer. You first have a dart of red light extending right across the vessel. Then you come to a region of the spectrum for which the fluid is excessively opaque, and the red light, which is produced by the action of the incident light on the fluid in some way or other, cannot therefore extend very far into the fluid. Then you come to a region where the fluid although still opaque is comparatively transparent, and the red is traceable further inwards, and so on. It is noticed, however, after close observation, that where the incident rays are quickly used up the red light is very copious, and where they are more slowly used up the red light is not so strong.

In the figure some of the red bands are slightly shaded in the middle, to indicate that the red light is not so strong there as elsewhere. In the case of this fluid the effect is produced mainly by the visible spectrum, but it extends beyond that into the invisible region beyond the violet; so that the solution of quinine, and the alcoholic solution of the green colouring matter of leaves may, to a certain extent, be regarded as extreme cases of the same general phenomenon.

I will refer now to this diagram. It consists of two parts; the upper part is diagrammatic for the same reasons as before; that is, you do not see the upper half and the under half simultaneously, but you may see first one and then the other. When the green colouring matter is purified by a particular process which would take too long to describe, and you take rather a dilute solution of it, and analyse the transmitted light, you get these bands of absorption. When you allow the upper spectrum to enter a very dilute alcoholic solution in this manner, then the red light which is given out in the regions of the spectrum near which the fluid is comparatively transparent, is given out there comparatively slowly, and accordingly it is less brilliant in the neighbourhood of the surface than is that corresponding to regions of great absorption. When the fluid is extremely dilute, then the intensity of the light in the former part of the spectrum becomes so small that you hardly see it, but its intensity where the fluid uses up the incident light more quickly in producing this phenomenon may still be visible, so that you may get corresponding to the position of these bands of absorption in the transmitted light these red bands where the light is given out very copiously, the solution being so dilute that the red light given out in the intervals is hardly perceptible at all.

These phenomena are not very easily shown at a distance to a large audience, but they are very striking when you look at them, as two or three at a time may, in a room where the sunlight is introduced or where an electric lamp is used. I will, however, endeavour by and by to show some of them by the aid of the electric light, but I am afraid they will be seen very feebly compared to what I have described, which are the effects seen when the light is concentrated into a small space.

Now allow me to go back for a moment to explain one particular matter I forgot at the time. I said that the light transmitted through a solution of sulphate of quinine was ordinary light, and that if you examined it, and scrutinised especially the blue part of the spectrum, you would see nothing to account for the blue colour. If you examine it by a prism applied to the eye, you will, however, see that the violet, or more or less of the violet, is gone; instead of seeing as is usual the double line H, you will see the fluid terminate, according to the strength of the solution and the thickness looked through, more or less towards the violet, say on an average about half way between the fixed lines G and H.

Now the incident rays work on the fluid in such a manner as to cause it to give out light of a different kind altogether; a light which is found to be heterogeneous, or to consist of rays of various degrees of refrangibility. This rule I find to be universal, namely, that the refrangibility of the light in this process is *always lowered.* I have never found any exception to that, nor I believe has anyone since.[1] The rays which any one of these fluids is capable of giving out under the influence of these other rays are always of lower refrangibility, and you never have the refrangibility raised.

I will endeavour presently to show a test-tube with one of these solutions in part of the spectrum, though I cannot promise that it will be seen at a distance. The fact is I am accustomed to work with sunlight rather than with the electric light, and I require more preliminary trials than I allowed myself for making the thing succeed. Still I think you see that on interposing a test-tube with the solution of quinine in the beam from the electric lamp, after it has passed through the prism, it cuts off certain portions of the spectrum thrown on the wall beyond, forming a shadow which shows in what part of the rays proceeding to form the spectrum the tube is for the moment placed; the blue light with which the solution glows, commencing about the violet, is seen altogether beyond the region of the visible rays. Here is a solution of a substance obtained from the bark of the horse-chestnut which shows it still better. You observe the blue band beyond the visible spectrum altogether. Another instance is when we allow the beam of light to fall on a piece of red cloth, it shows an orange band beyond the visible rays.

[1] Calorescence, or the exhibition of light by a body intensely heated by the concentration upon it of invisible heat-rays, is in some respects so different from the phenomena of fluorescence or phosphorescence that I do not regard it as forming any exception to the rule.

I have been a little anticipating what was to come, namely, that these phenomena are not confined to fluids or clear solids, but that they can be seen in every case. I have shown you that in a spectrum if you separate out the rays from one another by prismatic refraction you can see the phenomena in the invisible rays. But there is another mode of separating light into two portions of which one is allowed to pass, which is easier in practice, and which exhibits some of these phenomena very beautifully—that is by analysing it by absorption. For instance, I have here a very deep blue glass which cuts out most of the visible light, but it admits the violet and certain invisible rays beyond very copiously. It is a cobalt blue glass, and here is a yellow glass. I will analyse the light, not by a prism, but simply by absorption. This jar at present contains nothing but water. Now I will put the blue glass on to the electric lamp, and I have here a solution obtained from the bark of the horse-chestnut, a little of which I will drop into the jar. If you make a decoction of the bark, which contains a good deal of tannin, the solution soon becomes brown. It contains however two crystallizable substances, called esculin and fraxin, which can be obtained chemically pure. The alkaline solutions of these bodies have this power in a high degree. You can get rid of the tannin by making a decoction, and when cold adding some persalt of iron or salt of alumina, precipitating by ammonia, and filtering, and you then get this beautiful solution, which will keep very fairly. I will pour some of this into the water, and as it sinks down it forms a beautiful blue cloud. If I hold the blue glass so as to intercept the incident rays hardly any diminution will be perceived, while the yellow glass cuts off most of the rays by which the effect is produced ; but if I put the yellow glass between the jar and your eyes, a great deal of the light is transmitted. The general effect is shown very well by means of these glasses. Here also are some jars containing some fluorescin and other fluids which can be tried in the same way. A coloured medium will absorb in a different manner the rays that fall on the fluid and the rays coming from it. That leads to one method of observation, which does not require the apparatus which I have hitherto supposed, but is exceedingly simple and at the same time very effective. You do not even require sunlight, you can work with ordinary daylight. Suppose you have a room which you can darken, and that you are at liberty to cut a hole four or five inches square in the shutter, under which it is convenient to screw on a ledge for the sake of supporting the object to be examined, and that you cover the hole by a suitable glass. The most useful generally is a dark blue coloured by cobalt, or a dark violet coloured by manganese. The blue does better for some things and the violet for others. Cover the hole in the shutter with the deep coloured glass or, as is occasionally better, with a solution of a salt of copper, such as the nitrate, which is more convenient than the sulphate on account of its great solubility. Suppose you have daylight filtered as it were through the deep blue or violet glass; then if you place in front of the glass a test-tube containing a solution of quinine in dilute sulphuric acid, or a solution obtained from the bark of the horse-chestnut with a little ammonia, you will see this blue phosphorescent-looking light to perfection. But supposing you have not a window-shutter which you can make a hole in, still you can get on very well with an old packing-case. You knock off part of the top of it, so that you may look in, and saw off a portion obliquely parallel to the opposite top edge. and on the slanting rectangular hole thus formed you nail a piece of board, making a window in it four or five inches square, with a little ledge to keep the glass with which you cover it from slipping down You place it near the window and cover your head with a dark cloth as if you were looking into a camera obscura, and so you can see the phenomenon to perfection.

If you want to demonstrate that it is really this phenomenon you are dealing with, it is desirable to have a second glass in a certain sense complementary to the first. If we could pick out media which absorbed light just in the way we wished, we should choose a coloured glass perfectly opaque from the red end up to the blue or violet, and perfectly transparent beyond, and a second glass perfectly opaque for those rays for which the first was transparent, and *vice versâ*. But as we cannot make media to command to absorb what parts of the spectrum we like, we must make use of the best which the colouring matters of nature afford us; and if you take a blue glass and a yellow glass they will in most cases answer the purpose sufficiently well. Suppose then you have a dark glass on a window-shutter and you have in front of it a substance to be examined, and it gives out this beautiful phosphorescent light. In general this may be at once distinguished from mere scattered light; but to make sure of it use your yellow glass, and place it between the blue and the substance you are examining. If it is well chosen it will cut off almost all the effect. Then place it between your eye and the medium which is shining with this phosphorescent light and you will see it quite plainly. The difference of effect with this additional glass in the two positions proves that you have really to deal with this peculiar phenomenon, and enables you to at once distinguish it from some appearances which at the first glance resemble it very much. If you put a minute quantity of a solution of proto-chloride of tin into a large quantity of common water, the mixture will have a bluish look by reflected light, and if you condense sunlight upon it you will get a beam somewhat like what you do when you receive a beam on the solution of sulphate of quinine. This however is merely scattered light; and that it is so is shown at once when you come to make experiments upon it in which you strain the incident light. For example, if you place the mixture inside your darkened chamber in lieu of the solution of quinine, the difference will appear in a moment. The mixture will merely give out a little light of a deep blue colour, which is scattered light, whereas the solution of quinine will be lighted up with this beautiful light that you see. I may mention a very simple and pretty experiment which can be made in that way. Take a bit of common horse-chestnut bark, float it in a glass of still water in which a drop of ammonia had been mixed; the peculiar substances contained in the bark will begin to be dissolved, the solution will descend, and you will see streams of descending blue light. If you can obtain specimens of these substances esculin and fraxin, a minute quantity of the two thrown together on the water instead of the bark looks very pretty. The substances will form little luminous specks here and there on the surface, which will give rise to descending streams of blue and greenish light.

Now there is another way of testing the change of refrangibility almost without apparatus, by using your darkened chamber with a piece of blue glass in the window. Suppose that in front of the blue glass you place a piece of white earthenware, such as a saucer turned upside down. If you hold a slit at arm's length and view it through a prism, in the first instance aiming at the blue glass and looking up at the sky, you will see the sort of light transmitted. The brighter parts of the original spectrum will be almost entirely wanting, but you will see the violet, much of the blue, and the faint extreme red which is freely transmitted, and if the glass be not very deeply coloured a little faint greenish yellow which is not yet wholly absorbed. If you now aim at the white plate instead of the sky, you will see just the same spectrum as before, only not quite so strong. Now suppose you lay on the white plate a little bit of ordinary scarlet cloth, hold the slit close to that, and aim at both the cloth and the white plate, so as to get from different parts of the slit a spectrum of the light coming from each. This particular cloth in the blue field would look red On examining the joint spectrum, the part seen by projection of the slit on the plate will appear as just described, while that seen by projection on the scarlet cloth will show a prolongation of the extreme red, and a great deal of bright light where there is none in the incident light, while the violet part will be nearly black.

This diagram, which was made for another purpose, may serve to exhibit what you would see in that particular case. It really represents what you see by looking through a crystal of nitrate of uranium placed immediately behind the slit with which you aim at the white light sifted through a blue medium. There are certain bands of absorption where there is a maximum of opacity in the incident light; and when you analyse the beam of light which comes through you see in the transmitted rays there are certain dark bands of absorption; but over and above that, there is light created with a refrangibility less than exists at all in the incident beam, and in the particular case of the salt of uranium the prismatic composition of this light is very peculiar, its spectrum consisting of bright bands.

Now as I want to show you how to make experiments yourselves without apparatus, I may mention that supposing you have one of these solutions in a test-tube, you very much increase the effect by plunging the test tube in water and looking at it downwards nearly parallel to the test-tube. The reason of that is that the incident rays fall upon the fluid and cause it to give out light in all directions, blue light, or whatever else it may be, according to the nature of the fluid; but when the water is not there, a portion of the light so given out does not enter the eye at all, but suffers total internal reflection at the outer surface of the tube. On the other hand, if you look inside the tube the light suffers absorption on the part of the fluid itself. It does not much signify in the case of sulphate of quinine, which is sensibly transparent, but if you examine any coloured fluorescent fluid looking down the tube inside, you lose light from defect of transparency, the light being absorbed by the fluid; whilst if you look outside you lose a great deal by the total internal reflection at the surface of the glass. But if you plunge the test-tube into water, and look down from the outside, any of the emitted light which gets into the glass of the tube is able to get out again, so that you can look down from above in a very slanting direction and still get all the light, and as the stratum which emits the light is seen very much foreshortened, the brightness of the light is thereby increased.

Now as to the cause of this phenomenon. From the first I believed the cause to be this: that the incident rays so act on the ultimate molecules of the body as to throw them into a state of agitation, which agitation they in their turn are capable of communicating to the ether. Everybody now, I believe, considers that light is produced by the vibration of a certain subtle medium, which we call the luminiferous ether, and I will take a dynamical illustration of the phenomenon according to this view. Suppose you had a number of ships at rest on an ocean perfectly calm. Supposing now a series of waves, without any wind, were propagated from a storm at a distance along the ocean, they would agitate the ships, which would move backwards and forwards; but the time of swing of the ship would depend on the time of its natural oscillation, and would not necessarily synchronise with the periodic time of the waves which agitated the ship in the first instance. The ship, being thus thrown into a state of agitation, would itself become a centre of agitation, and would produce waves which would be propagated from it in all directions. This I conceive to be a rough dynamical illustration of what takes place in this actual phenomenon, namely, that the incidence of etherial waves causes a certain agitation in the ultimate molecules of the body, and causes them to be in their turn centres of agitation to the ether; in fact that the incident light renders the medium so to speak self-luminous, so long as it is under the excitement of the incident light. That is the view which I maintained from the first, and which is clearly expressed in my original memoir, which was published in the *Philosophical Transactions* of 1852. There is one phenomenon, that of phosphorescence, which I felt from the first to be exceedingly analogous to that which is now known by the name of *fluorescence*, a word I suggested in that original memoir, derived from fluor spar, which was one of the first minerals in which the phenomenon had been observed, as the analogous term, opalescence, is derived from the name of the mineral opal. I am unable to draw any sharp line of demarcation between fluorescence and phosphorescence. So far as I had observed, the effect was only of instantaneous duration, although, as I have expressly stated, I had not made experiments on a revolving mirror to determine whether a finite duration could be perceived. With regard to the explanation of the law which I believed to be universal, that in this phenomenon the refrangibility is always lowered, that is to say, the light coming out is always of lower refrangibility than the incident light, I offered a certain conjecture, which I did not hold to very tightly, and I have somewhat changed my views in that respect; but I held from the first that the effect is not a direct but an indirect one; that the light is not simply reflected from the ultimate particles of bodies. It is curious that some two or three writers have attributed to me the notion that in this phenomenon the light reflected from the molecules of the body was changed in refrangibility. They have attributed that notion to me, and then contended against it; but if you will allow me to read a short passage from my original paper, it will show that I am not responsible for that. I wrote these words: "In considering the cause of internal dispersion, we may, I think, at once discard all supposition of reflections and refractions of the vibrations of the luminiferous ether amongst the ultimate molecules of bodies. It seems to me quite contrary to dynamical principles to suppose that any such causes should be adequate to account for the production of vibrations of one period from vibrations of another." Having written that, I am not responsible for the view which has been so wrongly attributed to me. I can only account for it in this way. I suppose it was from the title I gave my paper, "On the change of refrangibility of light," which I chose because undoubtedly the most striking part of the phenomenon, which had not been hitherto suspected, was that the light given out was of a different refrangibility from the light going in. With regard to the duration of the phenomenon, I thought it *possible* that, though very large compared with the time of a single luminous vibration, it might elude our means of observation; but subsequently Mons. E. Becquerel showed, by a very ingenious instrument, which is here on the table, which he calls a phosphoroscope, that the phenomenon is really of appreciable duration. The light enters at one side, and falls on a cell containing the substance to be examined, in this case a salt of uranium enclosed between a pair of discs constituting a double fly with holes of a somewhat sectorial shape, so arranged that the holes in the one exactly correspond with the spaces between the holes in the other. When you turn the wheel round, supposing there is no substance there, you see no light, because you are always looking across a plate of metal. At one time there is a hole in the front disc, which is covered by the second plate, and when there is a hole in the second plate it is covered by the front disc; a series of holes coming alternately in the two discs. But supposing a substance is interposed, and the light is let in, and you turn the wheel, the illumination is let on and cut off alternately with great rapidity; but you see the light, not at the moment when the body is illuminated, but a small fraction of a second afterwards, through the hole which is opposite your eye; in that way you see it a very short space of time after it has been lit, so to speak, by the incident light; it gets a number of doses of light in one rotation, and you get a number of glimpses of it immediately afterwards. In that way many substances which show this phenomenon appear luminous, and you see them by the light which has been treated in this manner. I may mention also that even a simple revolving mirror will show the duration of the effect in such cases as the salts of uranium and solids in general. If you use an ordinary electric machine as a source of illumination, giving a succession of sparks, or an induction coil with a Leyden jar in connection with the two terminals, which gives a momentary discharge, you can observe the substance in a rapidly revolving mirror, and in that way you get a momentary view of the substance by reflected light, while the illumination due to fluorescence, in case it has an appreciable duration, is drawn out into a broad gleam; so that even without an instrument of the kind now on the table the duration of the effect can be manifested by experiment. The duration of the effect, I may observe, has not as yet in any instance been demonstrated experimentally in the case of a liquid.

When epipolic dispersion was referred to a change of refrangibility of light, there were some older experiments which at once received their explanation. For instance, Sir John Herschel himself, on throwing a pure spectrum on turmeric paper, had noticed a great prolongation of the ordinary visible spectrum. But he supposed that this was due to the ultra violet rays, which were directly reflected into the eye; and he speculated whether there might not be a repetition of the colours of the ordinary spectrum. This, however, proved to be a phenomenon of the kind I have just described, fluorescence, or, if you like so to call it, phosphorescence, as I am persuaded that fluorescence is nothing but phosphorescence of brief duration. Mons. E. Becquerel went still nearer to the actual phenomenon, for he was making experiments on substances which show phosphorescence after exposure to light, and observed that some of them were specially luminous when light fell upon them and was acting upon them. Nevertheless, although he correctly explained what he witnessed in these cases, from connecting it too closely with phosphorescence, he failed to perceive the full bearing of his own observation; and though he had actually under his hands the solution of quinine, and had discovered by means of photography the intense absorbing action of that fluid on the invisible rays, and expressly mentioned the "dichroism" of the solution, he never dreamt of putting the two things together, and showing that the peculiar coloured light exhibited in this and other allied instances, which were matters of ordinary observation,[1] had an origin hitherto unsuspected.

I have here some phosphorescent tubes which have been lent to me, which you will see retain the luminosity for some time in the dark after the light of the electric lamp has been allowed to play upon them. The most phosphorescent substances are certain sulphides of metals of alkaline earths, though it is said that certain impurities contribute to the effect rather than otherwise.

In the course of my experiments I was led to see that glass was by no means transparent in regard to the most refrangible of the rays I had to deal with. I procured accordingly prisms and lenses of quartz, with which to form a pure spectrum. On applying them to the solar spectrum, the invisible rays were seen to extend far beyond anything I had ever seen before, and showed a continuation of Fraunhofer's lines that is represented on these maps, which were originally drawn for an evening lecture I gave on the subject for the British Association at Belfast in 1852. In the spring of the next year, while preparing for a lecture at the Royal Institution, in the laboratory of that institution, along with Faraday, though I had expected beforehand to obtain a very long spectrum by the use of the electric light, I was utterly surprised when I found the actual length of it. I used in the first instance a Leyden jar, and I could not but think at the first moment that there was some stray reflection of light, for if the visible spectrum was about one inch, the whole spectrum obtained by means of powerfully fluorescent substances, such as uranium glass, with the electric light, was about six or eight inches, which was a length I had not been at all prepared for.

[1] The very name "Schillerstoff," formerly given to æsculin, is derived from the property in question.

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