

WILLIAM ABNEY

COLOUR MEASUREMENT
AND MIXTURE

William Abney

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Содержание

PREFACE	5
CHAPTER I	6
CHAPTER II	8
CHAPTER III	13
CHAPTER IV	18
CHAPTER V	23
Конец ознакомительного фрагмента.	25

Sir William de Wiveleslie Abney

Colour Measurement and Mixture

PREFACE

Some ten years ago there were three measurements of the spectrum which I set myself to carry out; the last two, at all events, involving new methods of experimenting. The three measurements were: (1st) The heating effect; (2nd) the luminosity; and (3rd) the chemical effect on various salts, of the different rays of the spectrum. The task is now completed, and it was in carrying out the second part of it that General Festing, who joined me in the research, and myself were led into a wider study of colour than at first intended, as the apparatus we devised enabled us to carry out experiments which, whilst difficult under ordinary circumstances, became easy to make. On two occasions, at the invitation of the Society of Arts, I have delivered a short course of lectures on the subject of Colour, and naturally I chose to treat it from the point of view of our own methods of experimenting; and these lectures, expanded and modified, form the basis of the present volume.

As a treatise it must necessarily be incomplete, as it scarcely touches on the history of the subject – a part which must always be of deep interest. The solely physiological aspect of colour has also been scarcely dealt with; that part which the physicist can submit to measurement being that which alone was practicable under the circumstances.

W. de W. Abney.

South Kensington,
1st May, 1891.

CHAPTER I

Sources of Light – Reflected Light – Reflection from Roughened Surfaces – Colour Constants.

There is nothing, perhaps, in our everyday life which appeals more to the mind than colour, yet so accustomed are the generality of mankind to its influence that but few stop to inquire the "why and wherefore" of its existence, or its cause. To those few, however, there is a source of endless and boundless enjoyment in its study; for in the realms of physical and physiological science there is perhaps no other subject in which experiments give results so fascinating and often so beautiful. Although its serious study must be undertaken with a clear mind, a good eye, and a fair supply of patience, yet a general idea of the subject may be grasped by those who are possessed of but ordinary intelligence.

Colour phenomena are encountered nearly every day of one's life, and the fact that they are so frequently met with, prevents that attention to them, or even their remark. Who amongst us, for instance, has noticed the existence of what are called positive and negative after images, after looking at some strongly illuminated object, or would have gauged the fact that a certain portion of the nervous system can be fatigued by a colour, and give rise to images of its complementary, had not an enterprising advertiser, who manufactures a household necessary, drawn attention to it in a manner that could not be misunderstood.

If on an autumn afternoon we pass through a garden whilst it is still perfectly light, we can notice the gorgeous colouring of the flowers, and appreciate with the eyes the beauty of each tint. As evening comes on the tints darken, the darkest-coloured flowers begin to lose their colour, and only the brightest strike the eye. When night still further closes in every colour goes, though the outlines of the flowers may still be distinguished; and it would not be impossible, in some parts, to see a tiny speck of pale light upon the ground amongst them. This speck of light we should know from experience to be the light from a glow-worm. Why is it that we lose the colour of the flowers and recognize the tiny light from this small worm? The reason for the one is that in order for objects which are not self-luminous to be seen at all, light must fall on them and illuminate them, and the light which they reflect may be coloured if they possess the qualities to reflect coloured light. The glow-worm's light is seen, not because it does not emit light in the day-time, but because the eye, being limited in sensitiveness, is unable to distinguish it when it is flooded with the light of day. The glow-worm, however, is self-luminous, as is shown by the fact that it emits light in the dark, the light itself being slightly coloured if compared with that of day. That a candle-flame or the sun is self-luminous is an axiom, and need not be philosophised upon; but what must be impressed on the reader is, that though an object which requires to be illuminated to be seen, is not self-luminous, yet when illuminated it does in fact become a source of illumination to the eye, although the light is only light reflected from its surface. It is a point worth remembering that the rougher the surface of an object, the brighter to the eye it will be. That is, a coloured object when polished will be a bad secondary source of illumination, as the light incident upon it will be very nearly reflected from the surface, according to the ordinary laws of reflection; but if it be roughened it will become a much better source, as the roughnesses, though obeying the laws of reflection, will reflect light in every direction. A good example of this is an ordinary sheet of glass. Light from a source falling on its surface is scarcely reflected in any direction except in that determined by the ordinary laws of reflection, and it will be scarcely visible to the eye. Grind its surface, however, and the innumerable facets caused by the grinding will reflect light back to the eye in whatever position it be placed, and will thus be distinctly seen.

We may here premise that even the roughest surface will reflect a greater percentage – varying greatly according to the nature of the surface – of light in the direction which it would do if it were a

smooth surface than in any other; and in taking measurements of the light irregularly reflected from a rough surface, this fact must be borne in mind.

Not only must we know how colour is produced, but we must also be able to refer it to some standard which shall be readily reproduced, and which shall be unalterable. There are two variable factors which have to be taken into account in colour experiments: the first is the quality of light which illuminates the object, and the second is the sensitiveness of the eye which perceives it, as light is only a sensation which is recognized by the brain through the medium of the eye. We shall, as we go on, see that different qualities of light may cause objects to appear of different hues, and further that eyes may vary in perceptive power, to an extent of which the large majority of people are not aware. Hence it becomes necessary as far as possible to eliminate these variables.

The task which we have set ourselves to perform then, is first to find a suitable light for experimental work, and next to endeavour to refer colour to an eye which has no abnormal defects. This being accomplished, we have then to find means to measure the different constants which are involved in colour, and to refer the measurements to some standard. Colour constants are three, viz. hue, luminosity, and purity; and it will be seen that if these three are determined, the measurement of the colour is complete.

Perhaps the meaning of these terms may require to be explained. The hue of a colour is what in common parlance is often called the colour. Thus we talk of rose, violet, magenta, emerald green, and so on, but for measuring purposes the hue had best be referred to the spectrum colours as a standard (the means of doing so will be shortly explained), for they are simple colours, which can be expressed by numbers. Compound colours, which it may be said are invariably to be found in nature, being mixtures of simple colours, can be just as readily referred to the spectrum. By the luminosity of a colour we mean its brightness, the standard of reference being the brightness of a white surface when illuminated by the same white light. By the purity of a colour we mean its freedom from admixture with white light. An example of different degrees of purity will be found in washes of water-colours of different tenuity. Thus if we wash a sheet of paper with a light tint of carmine, the whiteness of the paper is not obliterated; if we pass another wash over it the whiteness of the paper is lessened, and so on. The lightest tint is that which is most lacking in purity.

CHAPTER II

A Standard Light – Formation of the Spectrum by Prisms and by the Diffraction Grating – Wave-lengths of the principal Fraunhofer Line – Position of Colours in the Spectrum.

As we have to turn to the spectrum for pure and simple colours, from which we may produce any compound colour we may wish to deal with, we will first consider the light with which we shall form it. A spectrum may be produced from any source of light, such as sunlight, limelight, the electric light, gaslight, or incandescence electric light, as also from incandescent vapours, or gases; but it is only a solid which is, or is rendered incandescent, that will give us a *continuous* spectrum, as it is called, that is, a spectrum which is unbroken by gaps of non-luminosity, or sudden change of brightness, throughout its length.

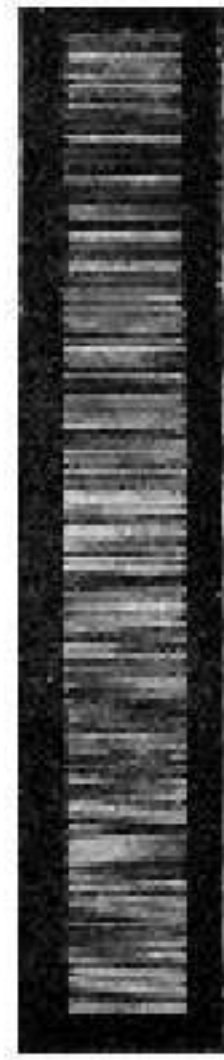


Fig. 1. – Spectrum of Sunlight.

The great desideratum for the study of colour is a light which not only gives a practically continuous spectrum, but one which is produced by the radiation of matter which is black when cold, and which can be kept at a constantly high temperature. We have purposely said "black"

in the sentence above, since it is believed that differently coloured bodies, when heated to equal temperatures, might not give the same relative intensities to the different parts of the spectrum, the variation being dependent on the colour of the heated body. A black body must always give the same visible spectrum when heated to the same temperature. The spectrum of sunlight ([Fig. 1](#)) is not continuous, as we find it crossed by an innumerable number of fine lines of varying breadth and blackness. This want of continuity would not be fatal to its adoption were it possible to use it outside the limits of our atmosphere, as then, unless the temperature of the sun itself changed, the spectrum produced would be invariable; but unfortunately the relative brightness or luminosity of the different parts of the spectrum varies from day to day, and hour to hour, according to the height of the sun above the horizon (see [Chap. VI.](#)); and its integral brightness varies according to the clearness of the sky. It is evident then, that, as a reference light, sunlight is most unsuitable, so we may dismiss it from our possible standards.



Fig. 2. – The Carbon Poles of an Electric Light.

By the process of elimination we may arrive at the light upon which we can rely, for the purpose we have in view, viz. the production of a spectrum of moderate size, and sufficiently bright to be well viewed when projected upon a screen. For some purposes, as for instance in becoming acquainted with the general character of the spectrum, a feebler light, such as gaslight, or light from electrical glow lamps, may be employed, since the spectrum may be viewed directly by the eye without the intervention of a screen. They have two drawbacks for our object: one being the want of general intensity, and the other the feeble luminosity of blue and violet rays in their spectrum (see [page 110](#)). The limelight we can also dismiss for want of steadiness. Its whiteness and luminosity varies according to the oxygen playing on the lime cylinder, rendering the relative intensities of the different parts of the spectrum so erratic as to make it unreliable. This leaves the (electric) arc-light as the only one which is really available. Remember how the arc-light is produced. A current of electricity passes between the ends of two thick black carbon rods, or poles as they are called, through an air space of small interval, and the passage of the current renders the tips of these rods white-hot ([Fig. 2](#)). The centre of the end of one pole, called the positive pole, where a crater-like depression is formed, is the part which attains the whitest heat, and its temperature seems to be constant, and to be that

of the volatilization of carbon. Numerous experiments have been made by the writer, and he has found that the light emitted by this crater in the positive pole is, within the limits of the error of observation, always of the same whiteness, and consequently gives a spectrum which is unvarying in the proportionate intensities of the different colours. When the experiments made to determine the luminosity of the spectrum are described, the method of ascertaining this will be readily understood.

In the spectrum produced by this light there are two places in the violet where there are bands of violet lines slightly brighter than the general spectrum. They are principally due to the light emitted from the incandescent vapour of carbon, which is volatilized and plays between the two poles (see [Fig. 2](#)); but as these bands are of but small visual intensity, and situated towards the limit of the visible spectrum, they do not interfere with eye-measures of colours, though they do, to a certain extent, to the analysis of radiation by photography. If we throw the positive pole a little behind the negative pole we can, however, considerably mitigate this evil. We can separate the carbon rods to such a degree that the white-hot crater faces the observer, and a good deal of the arc is hidden. This is well seen in the figure.

We have now described the light we have adopted, and the reasons for adopting it; and having obtained our light, we can now consider by what plan we shall form our spectrum. There are two ways open to us – one by glass prisms, and the other by a diffraction grating. Glass prisms separate white light, or indeed any light, into its components, from the fact that the refraction of each coloured ray differs from every other. Thus the red rays are least refracted, and the violet the most, and the yellow, green and blue are intermediate between them, being placed in the order of least refrangibility. Between these there is of course every shade of simple colour, one melting into the other. In order to form a pure and bright spectrum with prisms, in a room of limited dimensions, we have to use certain auxiliary apparatus which are not positively essential, though convenient. The real essentials to form a spectrum are a narrow slit, a glass prism, with perfectly plane faces, and a lens. If this be the only apparatus available, the slit must be placed at a long distance from the prism, the beam of light must pass through the slit on to the prism, and the lens must be placed at such a distance from the slit that it forms a sharp image on a screen. When the light passes through the prism, the screen will have to be rotated in the arc of a circle, so that its distance from the slit measured along the line of the ray to the prism, and from the prism to the screen, is the same as it would be without the intervening prism. An apparatus of this description is not convenient, however, as it requires much more space than is often available. If a lens be placed between the slit and the prism, at exactly its focal length from the former, the light entering the slit will, after passage through the lens, emerge as parallel rays, that is, they will emerge as they would do if the slit were placed at an infinite distance from the observer.

The focal length of this collimating lens need not be greater than twelve to eighteen inches, so that the great space required by the cruder apparatus is very much curtailed. The lens and slit are mounted one at each end of a tube of the necessary length, and are thus handy to use.

Instead of one prism two or three may be used, giving an angular dispersion of the spectrum two or three times respectively greater than that which would be given by only one prism; consequently to obtain a given length of spectrum with the increased dispersion, the focal length of the lens used to focus the image on the screen may be diminished.

The drawback to the use of prisms is that the dispersion of the red end of the spectrum is much less than that of the blue end, and is apt to give a false impression as to the relative luminosities of, and length of spectrum occupied by, the different colours. In some text-books it is told us that the diffraction grating gives us a dispersion which is in exact relation to the wave-length. This is not true, however, as it can only give one small portion in such relationship, and that only when it is specially set for the purpose. The subject of diffraction is one into which it would be foreign to our purpose to wander. We may say that for measures such as we shall make, it is handier to employ prisms, as the prismatic spectrum is more intense than the diffraction spectrum. This can be readily understood when we consider the subject even superficially. If we throw a beam of light on a grating which

contains perhaps some 14,000 parallel lines in the space of one inch in width, the lines being ruled on a plane and bright metallic surface, and receive the reflected beam on a screen, the appearance that is presented is a white central spot, together with six or seven spectra of gradually diminishing brightness on each side of it, all except the first pair overlapping one another. That these different spectra do exist can be readily shown by placing in the beam a piece of red glass, when symmetrical pairs of the red part of the spectrum will be found, one of each pair being on opposite sides of what will now be the central red spot. Half the light falling on the grating is concentrated in this central spot, and the remaining half goes to form the spectra; the pair nearest the central spot being the brightest. We thus are drawn to the conclusion that at the outside we can only have less than one-quarter of the incident light to form the brightest spectrum we can use. With two good prisms we use at last three-fourths of the incident light, so that for the same length of spectrum we can get at least three times the average brightness that we should get were we to employ a diffraction grating.

We must now refresh the reader's memory with a few simple facts about light, in order that our meaning may be clear when we speak of rays of different wave-lengths. Every colour in the spectrum has a different wave-length, and it is owing to this difference in wave-length that we are able to separate them by refraction, or diffraction, and to isolate them. Light, or indeed any radiation, is caused by a rhythmic oscillation of the impalpable medium which we, for want of a better term, call ether, and the distance between two of these waves which are in the same phase is called the wave-length of the particular radiation. The extent of the oscillation is called the amplitude, which when squared is in effect a measure of the *intensity* of the radiation. Thus at sea the distance between the crests of two waves is the wave-length, and the height from trough to crest the amplitude; and the intensity, or power of doing work, of two waves of the same wave-lengths but of different heights, is as the square of their heights. Thus, if the height of one were one unit, and of the other two units, the latter could do four times more work than the former. The waves of radiation which give the sensation of colour in the spectrum vary in length, not perhaps to the extent that might be imagined, considering the great difference that is perceived by the eye, but still they are markedly different. The fact that the spectrum of sunlight is not continuous, but is broken up by innumerable fine lines, has already been alluded to. The position of these lines is always the same, as regards the colour in which they are situated, and is absolutely fixed directly we know their wave-length; hence if we know the wave-lengths of these lines, we can refer the colour in which they lie to them. Now some lines of the solar-spectrum are blacker and consequently more marked than others, and instead of referring the colours to the finer lines, we can refer them to the distance they are from one or more of these darker lines, where these latter are absolutely fixed; in fact they act as mile-stones on a road.

In the red we have three lines in the solar spectrum, which for sake of easy reference are called A, B and C; in the orange we have a line called D, in the green a line called E, in the blue F, in the violet G, and in the extreme violet H. These lines are our fiducial lines, and all colours can be referred to them. The following are the wave-lengths of these lines, on the scale of **1/10,000,000** of a millimetre as a unit

A	7594
B	6867
C	6562
D	5892
E	5269
F	4861
G	4307
H	3968

When the spectrum is produced by prisms the intervals between these lines are not proportional to the wave-lengths, and consequently if we measure the distance of a ray in the spectrum from two

of these lines, we have to resort to calculation, or to a graphically drawn curve, to ascertain its wave-length. For the purpose of experiments in colour the graphic curve from which the wave-length can immediately be read off is sufficient. The following diagram (Fig. 3) shows how this can be done.

The names and range of the principal colours which are seen in the spectrum has been a matter of some controversy. Professor Rood has, however, made observations which may be accepted as correct with a moderately bright spectrum. If the spectrum be divided into 1000 parts between A in the red, and H, the limit of the violet, he makes the following table of colours.

Scale.	Colour.
0 to 149	Red.
149 to 194	Orange red.
194 to 210	Orange.
210 to 230	Orange yellow.
230 to 240	Yellow.
240 to 344	Yellow green and green yellow.
344 to 447	Green and blue green.
447 to 495	Azure blue.
495 to 806	Blue and blue violet.
806 to 1000	Violet.

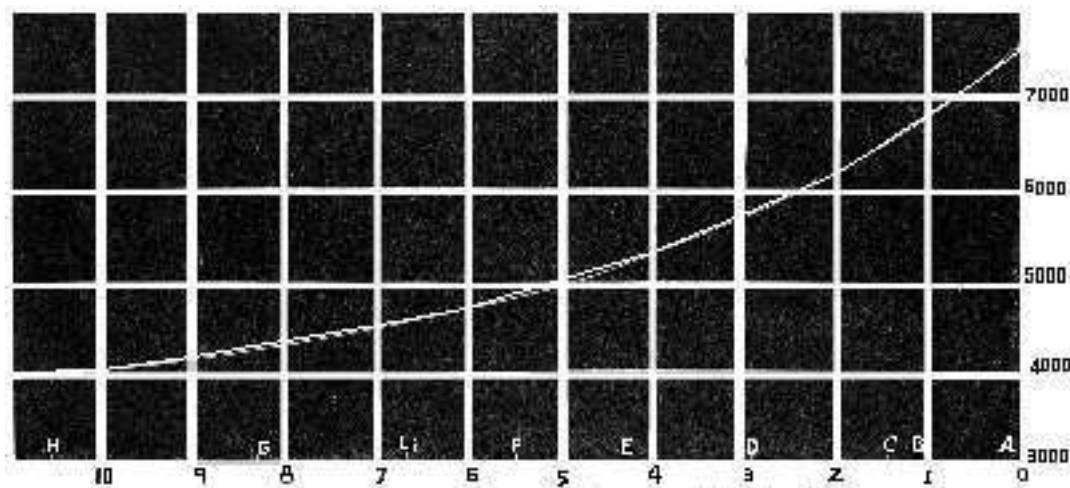


Fig. 3. – Curve for converting the Prismatic Spectrum into Wave-lengths.

In the above scale (Fig. 3) $A = 0$, $B = 74.0$, $C = 112.7$, $D = 220.3$, $E = 363.1$, $F = 493.2$, $G = 753.6$, $H = 1000$.

These are the main subdivisions of colour, but it must be recollected that one melts into the other. When the spectrum is very bright the colours tend to alter in hue; thus the orange becomes paler, and the yellow whiter, and the blue paler. On the other hand, if the spectrum be diminished in brightness the tendency is for the colours to change in the opposite direction. Thus the yellow almost disappears and becomes of a green hue, whilst the orange becomes redder, and the spectrum itself becomes shorter to the eye than before.

Let us strictly guard ourselves, however, from the criticism that all eyes see not alike. Suffice it to say that the above table is correct for the ordinary or normal eye, and does not necessarily apply to those who have defective vision as regards colour sensation.

CHAPTER III

The Visible and Invisible Parts of the Spectrum – Methods for showing the Existence of the Invisible Portions – Phosphorescence – Photography of the Dark Rays – Thermo-Electric Currents.

We are apt to forget, when looking at the spectrum, that what the eye sees is not all that is to be found in the prismatic analysis of light. The spectrum, it must be recollected, is not limited to those rays which the eye perceives. There are rays both beyond the extreme violet and below the extreme red, which exist and which exercise a marked effect on the world's economy. Thus, rays beyond the violet are those which with the violet and the blue rays principally affect vegetation, enabling certain chemical changes to take place which are necessary for its growth and health; whilst the rays below the red are those possessing the greatest amount of energy, and if they fall upon bodies which absorb them, as very nearly all bodies do to a certain extent, they heat them. The warmth we feel from sunlight is principally due to the dark rays which lie below the red of the spectrum.

The existence of both kinds of these dark rays may be demonstrated in a very simple manner by the effect that they produce on certain bodies. For instance, there is a yellow dye with which cheap ribbon is dyed, which if placed in the spectrum and beyond the violet causes a visible prolongation of the spectrum. The light in the newly-seen and once invisible part of the spectrum is yellow, the colour of the ribbon itself. In fact, the whole of that part of the spectrum, which on the white screen is seen as blue and violet, becomes yellow, the red and green remaining unchanged. This change in colour is due to fluorescence, a phenomenon of light which Sir G. Stokes found was caused by an alteration in the lengths of the waves of light when reflected from certain bodies. It is not meant to imply by this that the wave-length of any ray falling on a body can be altered by reflection, but only that the body itself on which the rays fall emits rays of light which are not of the same wave-length as those which fall upon it. Now it is a fact that the rays that lie beyond the violet, and which are ordinarily invisible, are shorter than the violet rays, and that these are shorter than the yellow rays. It follows therefore that when, what we may now call, the ultra-violet rays fall on the yellow dyed ribbon, the waves emitted by it are so lengthened that they appear yellow to the eye instead of dark, violet, or blue.

We can also brush a solution of quinine on the screen, and immediately the place where the ultra-violet rays fall is illuminated by a violet light. We do not see the ultra-violet rays themselves, but only the rays of increased wave-length, which are emitted by their effect on the sulphate of quinine. Common machine oil as used for engines also emits greenish rays when excited by the ultra-violet rays, and a very beautiful colour it is. Fluorescence then is one means of demonstrating the existence of the ultra-violet rays – or Ritter's rays as they were formerly called, after their discoverer – in a very simple manner. The method of rendering the effects of the infra-red rays visible to the eye is also interesting. All, or at all events most, of our readers have seen Balmain's luminous paint. A glass or card coated with this substance, which is essentially a sulphide of calcium, when exposed to the light of the sun, or of the electric arc, and then taken into comparative darkness, is seen to shine with a peculiar violet-coloured light. If when thus excited we place it in a bright spectrum for some little time, we shall find on shutting off the light that where the ultra-violet and blue fell on it, the violet light is intenser than the light of the main part of the screen; where the yellow fell there is neither increase or diminution in brightness; but that in the red it becomes darker, and also beyond the limit of the visible spectrum, indicating the existence of rays beyond, which through their greater length have not the power of affecting the eye. If the spectrum be shut off, however, very soon after it falls on the plate, it has been asserted that the red and infra-red rays have increased the brightness of that particular part of the plate on which they fell. At first these two observations seem to contradict one another; they do not in reality. We may expose a tablet of Balmain's paint to light, and place a heated

iron in contact with the back of the plate; we shall then find that the iron produces a bright image of its surface on a less bright background. This bright image will gradually fade away, and the same space will eventually become dark compared with the rest of the plate. The reason of this is clear. When light excites the paint a certain amount of energy is poured into it, which it radiates out slowly as light. When the hot iron is placed in contact with it, the heat causes the light to radiate more rapidly, and consequently with greater intensity, at the part where its surface touches, and the energy of that particular portion becomes used up. When the energy of radiation of this part becomes less than that of the rest of the tablet, its light must of necessity be of less brightness than that of the background, with which the heated iron has had no contact. For this reason the image of the iron subsequently appears dark. We shall see presently, and as before stated, that the principal heating effect of the spectrum lies in the red and infra-red, and it is owing to the heating of the paint by these rays that the image might be at first slightly brighter than the background, and subsequently darker.

There is another way in which the existence of both the ultra-violet and infra-red rays can be demonstrated, and that is by means of photography. If we place an ordinary photographic plate in the spectrum and develop it, we shall find that besides being affected by the blue and violet rays, it is also affected by the rays beyond the violet, the energy of these rays being capable of causing a decomposition of the sensitive silver salt. If quartz prisms and lenses be used, and the electric light be the source of illumination, the ultra-violet spectrum will extend to an enormous extent. A more difficult, but perhaps even more interesting means of illustrating the existence of the infra-red rays, and first due to the writer, can be made by means of photography. It is possible to prepare a photographic plate with bromide of silver, which is so molecularly arranged that it becomes capable of being decomposed not only by the violet and blue rays, but also by the red rays, and by those rays which have wave-lengths of nearly three times that of the red rays. It would be inappropriate to enter into a description of the method of the preparation of these plates. Those who are curious as to it will find a description in the Bakerian lecture published in the *Philosophical Transactions of the Royal Society* for 1881. With plates so prepared it has been found possible to obtain impressions in the dark with the rays coming from a black object, heated to only a black heat.

That these dark rays possess greater energy or capacity for doing work of some kind than any other rays of the spectrum, can be shown by means of a linear thermopile (Fig. 4), if it be so arranged as to allow only a narrow vertical slice of light to reach its face.

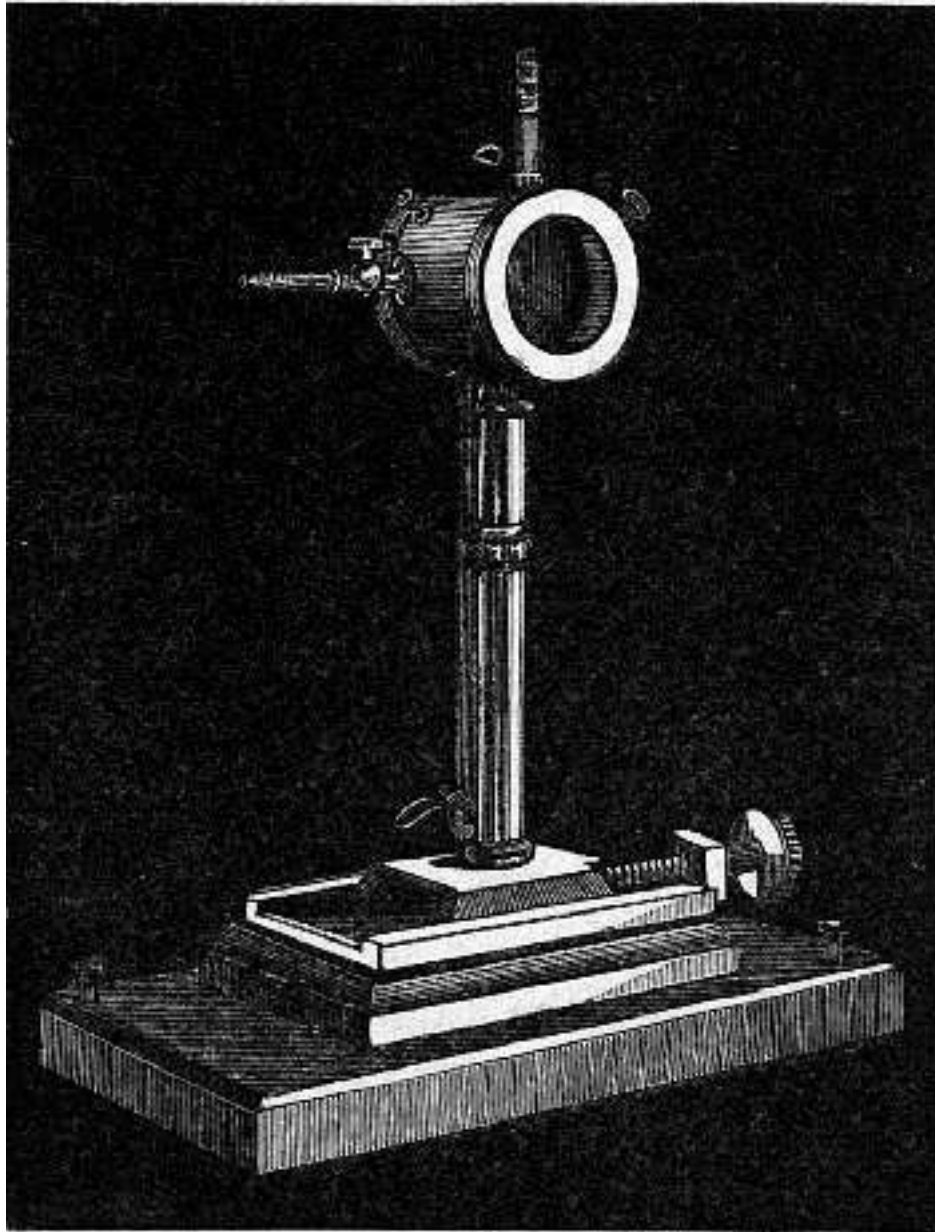


Fig. 4. – The Thermopile.

The principle of the thermopile we need not describe in detail. Suffice it to say that the heating of the soldered junctions of two dissimilar metals (there are ten pairs of antimony and bismuth in the above instrument) produces a feeble current of electricity, which, however, is sufficient to cause a deflection to the suspended needle of a delicate galvanometer. To the needle is attached a mirror weighing a fraction of a grain, and the deflections are made visible by the reflection from it of a beam of light issuing from a fixed point along a scale. The greater the heating of the junctions of the thermopile, within limits which in these cases are never exceeded, the greater is the current produced, and consequently the greater is the deflection of the mirror-bearing needle, and of the beam of light along the scale. In order to get a comparative measure of the energies of the different rays, it is necessary that they should be completely absorbed. Now the junctions themselves of the pile being metal, and therefore more or less bright, will not absorb completely, but if they be coated with a fine layer of lamp-black, the rays falling on the pile will be absorbed by this substance, and their absorption will cause a rise in temperature in it, and the heat will be communicated to the thermopile.

If we make a bright spectrum, and one not too long, say three inches in length, and pass the linear thermopile through its length, we shall find that when the galvanometer is attached, the galvanometer needle will be differently deflected in its various parts. The deflection will be almost insensible in the violet, but sensible in the blue, rather more in the green, still more in the yellow, and it will further increase in the red. When, however, the slit of the thermopile is placed beyond the limit of the visible spectrum, the deflection enormously increases, and will increase till a position is reached as far below the red as the yellow is above it. After this maximum is reached, by moving the pile still further from the red, the galvanometer needle will travel towards its zero, and finally all deflection will cease. At this point we may suppose we have reached the limit of the spectrum, but if rock-salt prisms and lenses be used, the limit will be increased. What the real limit of the spectrum is, is at present unknown; Mr. Langley with his bolometer, and rock-salt prisms, an instrument more sensitive than the thermopile, must have nearly reached it.

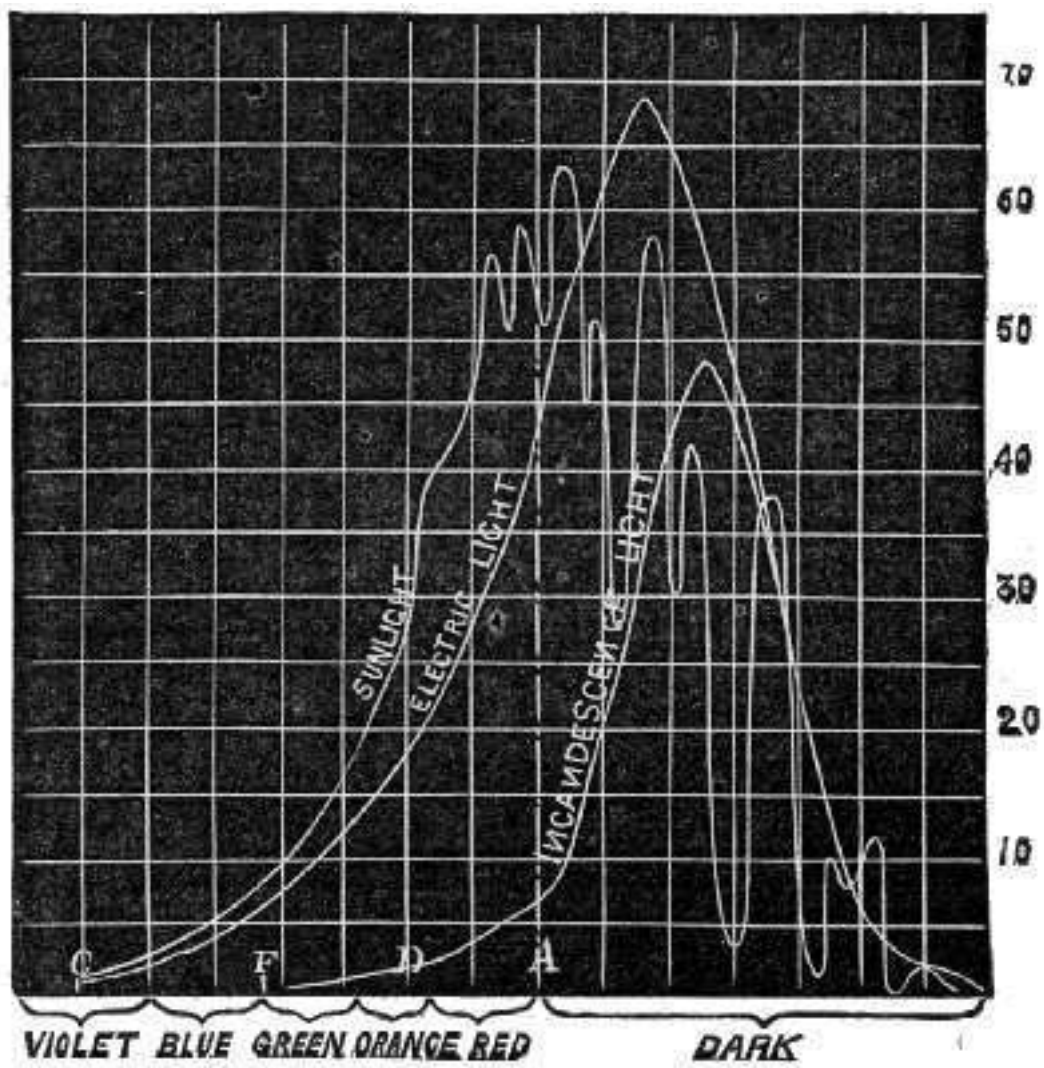


Fig. 5. – Heating effect of different Sources of Radiation.

The above figure is a graphic representation of the heating effect of the spectrum of the electric light, sunlight, and the incandescence electric light, on the lamp-black coating of the thermopile, as shown by the galvanometer. The vast difference between the heating effect of the visible rays of the first two sources compared with the last is clearly indicated.

Since every ray may be taken as totally absorbed, the heating of the lamp-black is a measure of the energy or the capacity of performing work of some description, which they possess. Waves of the sea do work when they beat against the shore, and they do work when they lift a vessel. If we notice a ship at anchor we shall find that behind the vessel and towards the shore the waves are lowered in height or amplitude; the energy which they have expended in raising the vessel of necessity causes this lowering. In the same way the waves of light, after falling on matter whose molecules or atoms are swinging in unison with them, are destroyed, and the energy is spent in either decomposing the matter into a simpler form at first – though the subsequent form may be more complex – or in raising its temperature. As lamp-black or carbon is in its simplest form, the only work done upon it by the energy of radiation is the raising of its temperature, and it is for this reason that this material is so excellent for covering the junctions of the pile. The eye evidently does not absorb all rays, since only a limited part of the spectrum is visible, and it would be useless to take a measure of the heating effect of lamp-black for the visible part of the spectrum as a measure of its luminosity, since the latter fades off in the red – the very place in which the heat curve rises rapidly.

CHAPTER IV

Description of Colour Patch Apparatus – Rotating Sectors – Method of making a Scale for the Spectrum.

Before proceeding further we must describe somewhat in detail two or three pieces of apparatus to be used in the experiments we shall make.

The first piece was devised by the writer a few years ago, and has got rid of several objections which existed in older pieces of apparatus. It is not only useful for lecture purposes, but also for careful laboratory work. The ordinary lecture apparatus for throwing a spectrum on the screen is of too crude a form to be effective for the purpose we have in view; the purity of the colours seen on the screen is more than doubtful, and this alone unfits it for our experiments. If we want to form a pure spectrum we must have a narrow slit, prisms with true, flat surfaces, and lenses of proper curvature. As a rule the ordinary lecture apparatus for forming the spectrum lacks all of these requisites.

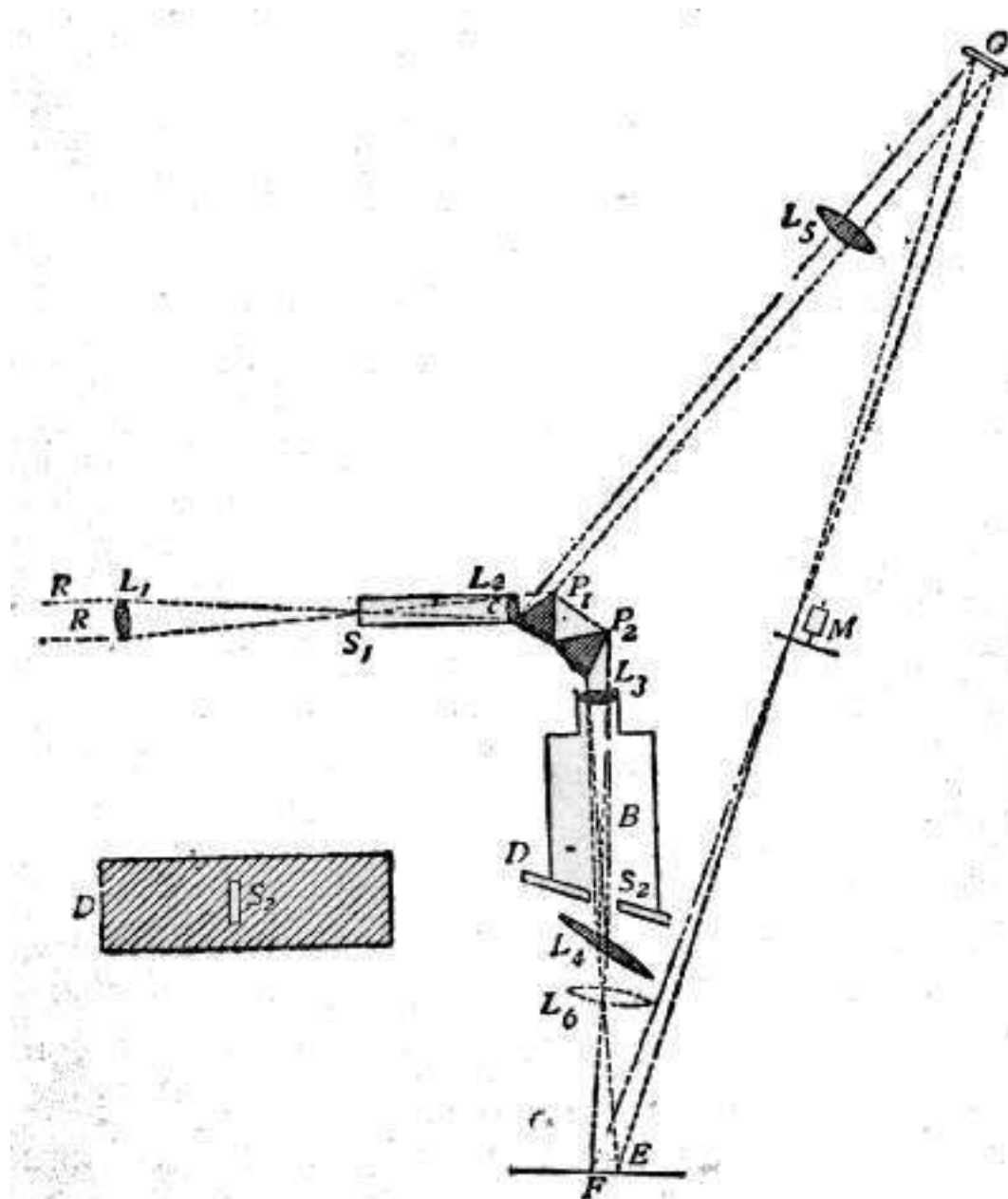


Fig. 6. – Colour Patch Apparatus.

The accompanying diagram (Fig. 6) will give an idea of the apparatus we shall employ. On the usual slit S_1 of a collimator C is thrown, by means of a condensing lens L_1 , a beam of light, which emanates from the intensely white-hot carbon positive pole of the electric light. The focus is so adjusted that an image of the crater is formed on the slit. The collimating lens L_2 is filled by this beam, and the rays issue parallel to one another and fall on the prisms P_1 and P_2 , which disperse them. The dispersed beam falls on a corrected photographic lens L_3 , attached to a camera in the ordinary way. It is of slightly larger diameter than the height of the prisms, and a spectrum is formed on the focusing-screen D , which is slewed at a slight angle with the perpendicular to the axis of the lens L_3 . This is necessary, because the focus of the least refrangible or red rays is longer than that of the more refrangible or blue rays. By slewed the focusing-screen as shown, a very good general focus for every ray may be obtained. When the focusing-screen is removed, the rays form a confused patch of parti-coloured light on a white screen F , placed some four feet off the camera. The rays, however, can be collected by a lens L_4 , of about two feet focus, placed near the position of the focusing-screen,

and slightly askew. This forms an image on the screen of the near surface of the last prism P_2 ; and if correctly adjusted, the rectangular patch of light should be pure and without any fringes of colour. The card D slides into the grooves which ordinarily take the dark slide. In it will be seen a slit S_2 , the utility of which will be explained later on.

We shall usually require a second patch of white light, with which to compare the first patch. Now, although the light from the positive pole of the carbons is uniform in quality, it sometimes varies in quantity, as it is difficult to keep its image always in exactly the centre of the slit. If we can take one part of the light coming through the slit to form the spectrum, and another part to form the second patch of white light, then the brightness of the two will vary together. At first sight this might appear difficult to attain; but advantage is taken of the fact that from the first surface of the first prism P_1 a certain amount of light is reflected. Placing a lens L_5 , and a mirror G , in the path of this reflected beam, another square patch of light can be thrown on the same screen as that on which the first is thrown, and this second patch may be made of the same size as the first patch, if the lens L_5 be of suitable focus, and it can be superposed over the first patch if required; or, as is useful in some cases, the two patches may be placed side by side, just touching each other.

We are thus able to secure two square white patches upon the screen F , one from the recombination of the spectrum, and one from the reflected beam. If a rod be placed in the path of these two beams when they are superposed, each beam will throw a shadow of the rod upon the screen. The shadow cast by the integrated spectrum will be illuminated by the reflected beam, and the shadow cast by the latter will be illuminated by the former. In fact we have an ordinary Rumford photometer, and the two shadows may be caused to touch one another by moving the rod towards or from the screen. When the illumination of the two shadows by the white light is equal, the whole should appear as *one* unbroken gray patch. To prevent confusion to the eye a black mask is placed on the screen F with a square aperture cut out of it, on which the two shadows are caused to fall. If it be desired to diminish the brightness of either patch, it can be accomplished by the introduction of rotating sectors M , which can be opened and closed at pleasure during rotation, in the path of one or other of the beams.

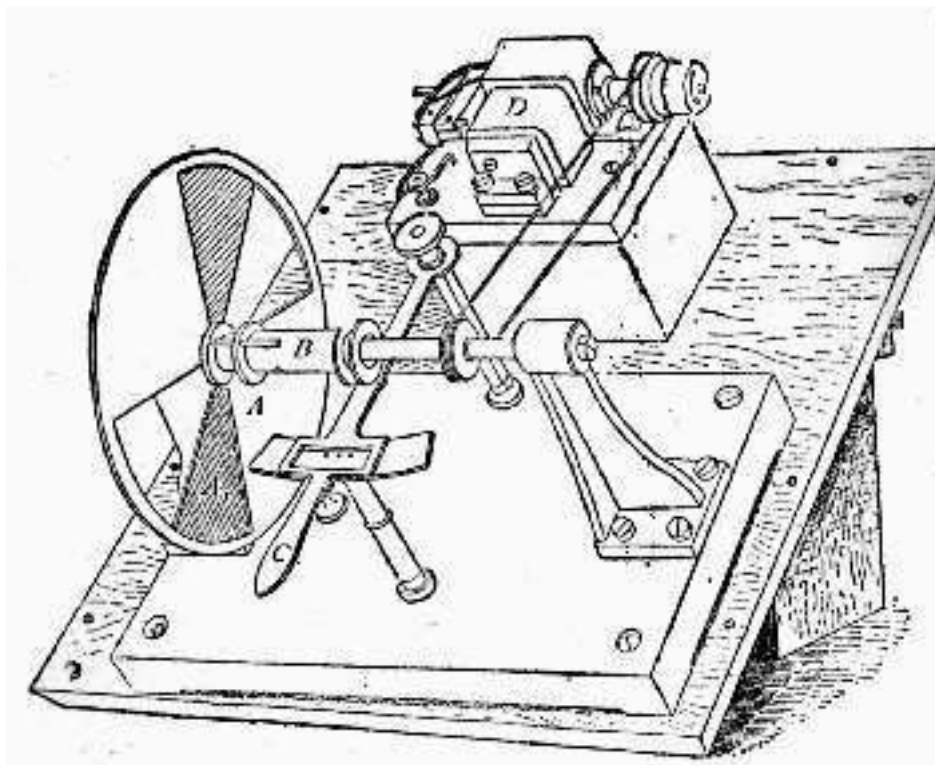


Fig. 7. – Rotating Sectors.

The annexed figure (Fig. 7) is a bird's-eye view of the instrument. A A are two sectors, one of which is capable of closing the open aperture by means of a lever arrangement C, which moves a sleeve in which is fixed a pin working in a screw groove, which allows the aperture in the sectors to be opened and closed at pleasure during their revolution; D is an electro-motor causing the sectors to rotate. To show its efficiency, if two strips of paper, one coated with lamp-black and the other white, are placed side by side on the screen, and if one shadow from the rod falls on the white strip, and the other shadow on the black strip of paper, and the rotating sectors are interposed in the path of the light illuminating the shadow cast on the white strip, the aperture of the sectors can be closed till the white paper appears absolutely blacker than the black paper. White thus becomes darker than lamp-black, owing to the want of illumination. This is an interesting experiment, and we shall see its bearings as we proceed, as it indicates that even lamp-black reflects a certain amount of white or other light.

Having thus explained the main part of the apparatus with which we shall work, we can go on and show how monochromatic light of any degree of purity can be produced on the screen. If the slit in the cardboard slide D be passed through the spectrum when it has been focused on the focusing-screen, only one small strip of practically monochromatic light will reach the screen, and instead of the white patch on the screen we shall have a succession of coloured patches, the colour varying according to the position the slit occupies in the spectrum. It should be noted that the purity of the colour depends on two things – the narrowness of the slit S_1 of the collimator, and of the slit S_2 in the card. If two slits be cut in the card D, we shall have two coloured patches overlapping one another, and if the reflected beam falls on the same space we shall have a mixture of coloured light with white light, and either the coloured light or the white light can be reduced in brightness by the introduction of the rotating sectors. If the rod be introduced in the path of the rays we shall have two shadows cast, one illuminated with coloured light, monochromatic or compound, and the other with white light, and these can be placed side by side, and surrounded by the black mask as before described.



Fig. 8. – Spectrum of Sodium Lithium and Carbon.

There is one other part of the apparatus which may be mentioned, and that is the indicator, which tells us what part of the spectrum is passing through the slit. Just outside the camera, and in a line with the focusing-screen, is a clip carrying a vertical needle. A small beam of light passes outside the prism P_1 ; this is caught by a mirror attached to the side of the apparatus, and is reflected so as to cast a shadow of the needle on to the back of the card D , on which a carefully divided scale of twentieths of an inch is drawn. To fix the position of the slit the poles of the electric light are brushed over with a solution of the carbonates of sodium and lithium in hydrochloric acid, and the image of the arc is thrown on the slit. This gets rid of the continuous spectrum, and only the bright lines due to the incandescent vapours appear on the focusing-screen (Fig. 8). Amongst other lines we have the red and blue lines due to the vapour of lithium; the orange, yellow (D), and green lines of sodium, together with the violet lines of calcium (these last due to the impurities of the carbons forming the poles). These lines are caused successively to fall on the centre of the slit by moving the card D , which for the nonce is covered with a piece of ground glass, and the position of the shadow of the needle-point on the scale is registered for each. A further check can be made by taking a photograph of these lines, or of the solar spectrum, and having fixed accurately on the scale any one of these lines already named, the position of the others on the scale may be ascertained by measurement from the photograph. Now the wave-lengths of these bright lines have been most accurately ascertained, in fact as accurately as the dark lines in the solar spectrum. Thus the scale on the card is a means of localizing the colour passing through the slit or slits. Should more than one slit be used in the spectrum the positions of each can be determined in exactly the same way. The most tedious part of the whole experimental arrangement with this apparatus is what may be called the scaling of the spectrum.

A fairly large spectrum may be formed upon the screen without altering any arrangement of the apparatus, when it has been adjusted to form colour patches. If a lens L_6 (see [Fig. 6](#)) of short focus be placed in front of L_4 (the big combining lens), an enlarged spectrum will be thrown upon the screen F , and if slits be placed in the spectrum the images of their apertures are formed by the respective coloured rays passing through them, so that the colours which are combined in the patch can be immediately seen.

CHAPTER V

Absorption of the Spectrum – Analysis of Colour – Vibrations of Rays – Absorption by Pigments – Phosphorescence – Interference.

We must now briefly consider what is the origin, or at all events the cause, of the colour which we see in objects. It is not proposed to enter into this by any means minutely, but only sufficiently to enable us to understand the subject which is to be brought before you. What for instance is the cause of the colour of this green solution of chlorophyll, which is an extract of cabbage leaves? If we place it in the front of the spectrum apparatus and throw the spectrum on the screen, we find that while there is a certain amount of blue transmitted, the green is strong, and there are red bands left, but a good deal of the spectrum is totally absorbed. Forming a colour patch of this absorption spectrum on the screen, we see that it is the same colour as the chlorophyll solution, and of this we can judge more accurately by using the reflected beam, and placing the rod in position to cast shadows. (The light of the reflected beam is that of the light entering the slit.) The colour then of the chlorophyll is due to the absence of certain colours from the spectrum of white light. When white light passes through it, the material absorbs, or filters out, some of the coloured rays, and allows others to pass more or less unaffected, and it is the re-combination of these last which makes up the colour of the chlorophyll. We have a green dye which to the eye is very similar in colour to chlorophyll, but putting a solution of it in front of the spectrum, we see that it cuts off different rays to the latter. It would be quite possible to mistake one green for the other, but directly we analyze the white light which has filtered through each by means of the spectrum, we at once see that they differ. Hence the spectrum enables the eye to discriminate by analysis what it would otherwise be unable to do. Any coloured solution or transparent body may be analyzed in the same way, and, as we shall see subsequently, the intensity of every ray after passing through it can be accurately compared with the original incident light. There are some cases, indeed the majority of cases, in which the colour transmitted through a small thickness of the material is different to that transmitted through a greater thickness. For instance, a weak solution of litmus in water is blue when a thin layer is examined, and red when it is a thicker or more concentrated layer. Bichromate of potash is more ruddy as the thickness increases. This can be readily understood by a reference to the law of absorption. Suppose we have a thin layer of a liquid which gives a purple colour when two simple colours, red and blue, pass through it, and that this thin layer cuts off one-quarter of the red and one-half of the blue incident on it, another layer of equal thickness will cut off another quarter of the three-quarters of red passing through the first layer, and half of the one-half left of the blue; we shall thus have nine-sixteenths of the red passing and only a quarter of the blue. With a third layer we shall have twenty-seven sixty-fourths of red and only one-eighth of blue left, showing that as the thickness of the liquid is increased the blue rapidly disappears, leaving the red the dominant colour. Now what is true of two simple colours is equally true of any number of them, where the rates of absorption differ from one another, and what is true for a solution is true for a transparent solid. In some opaque bodies, such as rocks, the reflected colour often differs slightly from that of the same when they are cut into thin and polished slices, through which the light can pass. The reason is that when opaque, light penetrates to a very small distance through the surface, and is reflected back, whilst in these layers the colour has to struggle through more coloured matter, and emerges of a different hue.

The question why substances transmit some rays and quench others, brings us into the domain of molecular physics. Of all branches of physical science this is perhaps the most fascinating and the most speculative, yet it is one which is being built up on the solid foundations of experiment and mathematics, till it has attained an importance which the questions depending on it fully warrants. We have to picture to ourselves, in the case in point, molecules, and the atoms composing them, of a size

which no microscope can bring to view, vibrating in certain definite periods which are similar to the periods of oscillation of the waves of light. At page 26 we have given the lengths of some of the waves which give the sensation of coloured light. Now as light, of whatever colour it may be, is practically transmitted with the same velocity through air which has the same density throughout, it follows that the number of vibrations per second of each ray can be obtained by dividing the velocity of light in any medium by the wave-length. The following table gives roughly the number of vibrations per second of the ether giving rise to the colours fixed by the dark solar lines.

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