Newton's Work in Physics.[1]

By Sir J. J. THOMSON, O.M., F.R.S.

THE middle of the seventeenth century, when Newton was born, was remarkable for an outburst in natural philosophy akin to that in literature at the Renaissance. New ideas, new inventions, new discoveries were coming forward both in England and on the Continent. The Royal Society had just been formed to discuss scientific questions and to witness scientific experiments. The soil had been prepared by the work of giants like Descartes, Hooke, Boyle, and Huyghens. To Descartes more than to any one else was this outburst of interest due. It was he who invented the ether; by his theory of vortices he had supplied a consistent and comprehensive theory in which it was conceivable all physical phenomena might find their place and explanation. His theory clothed with romance and fascination the dry bones of science; to see how it fitted into the theory made each new discovery furnish a most fascinating intellectual problem. Later there was much contention between Cartesians and Newtonians, but let us who are Newtonians acknowledge the debt science owes to Descartes, the man whose "Treatise on Geometry" attracted Newton to mathematics and, he said, gave a vaster idea of geometry and the use of algebra than it was possible for him to express or for one who had not read it to imagine.

I am to speak to-day about Newton's work in physics. I will begin by pointing out what is perhaps generally not realised, his skill in the practical as well as the theoretical part of physics. He was an excellent manipulator and experimenter, and liked using his hands. Almost the only recreation in which he seems to have indulged as a boy was to make little work-boxes and trinket cases for his girl friends. He made the first reflecting telescope with his own hands. In the "Optics" he writes about the methods of grinding lenses with a gusto and wealth of detail which show what an old hand he is at the game. When, as in one of the Queries, he discusses chemical questions, he revels in details known only to those who have spent long hours in a chemical laboratory. Mr. Humphrey Newton, who acted as his amanuensis and assistant from 1683 until 1689, says: "At the spring and fall of the leaf he used to employ about six weeks in the laboratory, the fire scarcely going out either night or day, he sitting up one night and I another till he had finished his chemical experiments, in the performance of which he was the most accurate, strict, exact." At this time Newton was working at the transmutation of metals, and I think it exceedingly probable that he had spent more time over this subject than in writing the "Principia."

Newton's great discovery—the splitting up of white light into a spectrum of different colours—was led up to by his seeking for a cause for the bad definition of the refracting telescopes of the time. This was generally attributed to what is called spherical aberration, the rays which pass through the outer parts of the lens not being brought to the same focus as those which pass through the centre; indeed, Descartes had worked out elaborate shapes for lenses in order to remedy this. Newton seems to have convinced himself that there was more in it than this, and was thus led to make his famous experiment. He passed a narrow beam of white light through a prism and found that what had been narrow and white before falling on the prism, after passing through it was spread out into a broad band showing all the colours of the rainbow —red at one end, blue at the other, and between them a gradation of different colours which he divided into seven classes, red, orange, yellow, green, blue, indigo, and violet. He took a narrow beam from this coloured band and let it pass through another prism, and found that it behaved quite differently from the original white beam, and that it was not split up into a broader beam. A narrow beam of red light before falling on the second prism was a narrow beam of red light after passing through it. Again starting with a narrow beam of white light he split it up into a spectrum; he then sent the spectrum through another prism like unto the first but turned the other way up, and reproduced the narrow band of white light again. He first "untwisted the shining robe of day" and then put it together again.

The chapters in the "Optics" where these experiments are described give one, I think, an impression of intellectual power almost unparalleled in the history of physics. Every experiment—nay, almost every sentence—clears up some essential point, and on reading them again a few days ago to refresh my memory, I was even more impressed than I had ever been before, and re-echo the advice of the late Lord Rayleigh, that "*every* student of

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[1] Address delivered in King's School, Grantham, on Mar. 19, at the commemoration of the two-hundredth anniversary of the death of Sir Isaac Newton.

physics should read the earlier parts of Newton's 'Optics.'"

It is one of the ironies of science that the outcome of a successful attempt to get at the root of the reason for the imperfections of the refracting telescope should have had the effect of delaying the improvement of that instrument for the best part of a century. Newton diagnosed the disease, but came to the conclusion that it was incurable. As the defect was due to the different coloured rays being differently bent when they passed through a lens, to effect a cure it was necessary to use two lenses, one bending the rays in one direction, the other in the opposite, and to try to adjust the shape and materials of these lenses so that the difference in the bending of, say, the red rays is the same as that of the blue. If the system is to act as a telescope there must be some bending of each of the rays, and this was the difficulty. Newton came to the conclusion that the difference in bending of two rays was always in the same proportion to the average bending whatever the material of the lens. From this it follows that when the difference in bending vanishes the whole bending does so too, so that the system ceases to act as a telescope.

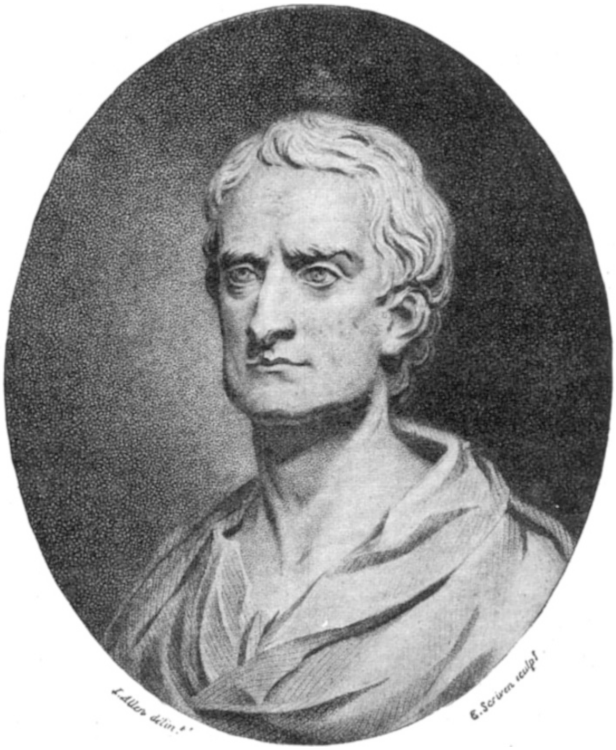

Fig. 7.—Bust of Newton in the Royal Observatory, Greenwich.

I think there were two reasons why Newton came to this conclusion: one was that the prisms he used were either prisms of light glass, or hollow prisms filled with water. He says that he used salt water in these prisms, and it is exceedingly probable that the dispersion of the light glass was almost identical with that of the salt water. There was, however, another reason which in my opinion was the one that influenced him most. Most of us, I think, on looking at the spectrum, would suppose that the number of colours to be distinguished is rather a question of the number of names our language supplies for different colours than of anything else. I do not think Newton held that opinion. He seems to have regarded the different colours—red, orange, yellow, green, blue, indigo, and violet as, so to speak, different genera and the light inside these colours as different species; he therefore attaches great importance to the places where one of these colours begins and the other ends. As "his own eyes are not very critical in distinguishing colour," he got a friend to measure the length of the different coloured spaces.

Now, unfortunately, the divisions between the different colours given by these measurements turned out to be in the same proportion as a string is divided between the end and the middle to give the divisions of the octave on the diatonic scale. Thus if the length of the string giving the lowest note is 1, and the length of the spectrum $\frac{1}{2}$, the length of the string giving the octave will be at the end of the violet, the length of the string giving the note next to the octave will be at the junction of the indigo and violet, the next at the junction of the indigo and blue, and so on. I think Newton was profoundly influenced by this view: he returns to it in his work on the colours of thin plates, and shows that the thicknesses of the plates which give the junction colours are proportional to the cube roots of the squares of the length of these chords on the diatonic scale. As on this view the widths of the different colours are always in fixed numerical ratios, the spectrum given by one substance will be exactly similar to that given by another; this means that the dispersion of all substances is the same and that an achromatic combination is impossible. It was, I think, the siren's song of these harmonics that lured Newton to this false conclusion. We must remember that Newton had no suspicion that the spectrum as he saw it, beginning at the red and ending at the violet, was not a complete entity, or that there was anything on either side of it; we know now that the visible spectrum is but a more or less arbitrary piece of a much larger structure.

It was, too, a very prevalent belief that these harmonics were the key to many of the mysteries of Nature. Kepler, for example, spent many years' work trying to express the motion of the different planets in terms of these harmonics. Holding these views, Newton came to the conclusion that the chance of making a refracting telescope was desperate; he abandoned what he called his glass work and devoted himself to developing the reflecting telescope. He was the first to construct such a telescope, though Gregory had provided him with a design for one on somewhat different lines. It is a remarkable illustration of Newton's influence on the science of his time, and for long after, that his error about achromatism was not corrected for more than fifty years, and that when at last this was done, it was due to the independent researches of two practical men, one a country gentleman and the other an instrument maker, and not to a philosopher attached to any seat of learning.

Newton next applied himself to the study of the colours of thin films, such as soap bubbles, and thin pieces of mica. These had previously been studied by Hooke and Boyle, and Hooke had published a theory of them in a paper which is one of the most remarkable in the history of optics; in it he foreshadows the principle of interference, and Young, the discoverer of this principle a century later, said that a knowledge of this paper would have materially hastened the discovery. The observations of Hooke and Boyle were entirely qualitative. Newton, as was his wont, reduced everything to definite numbers. His extraordinary powers of observation, and his genius for reducing to a few fundamental principles a mass of confused and perplexing phenomena, were never more conspicuous than in this investigation. The subject, which before he began his work had been but a medley of facts without any apparent connexion, was reduced by him to law and order; so much so that even now there are few better or clearer accounts of the fundamental phenomena, apart from their explanation, than that given in the "Optics." Surprisingly few of the great number of effects shown by these thin films escaped Newton's notice. He discovered the law connecting the thickness of the film with the colour it shows; he gives us the first measure of a quantity akin to the one we call now the wave-length of the light. He supposes that a ray of light as it travels through space alternates between two moods; when in one of these moods it falls on a surface it is reflected, when in the other it is transmitted. Each mood lasts while the ray travels a certain distance, and the ray is supposed to be always in one or other of the moods. He calls these moods 'fits' of easy transmission and reflection, and the quantity he measured is the space passed over by light on the duration of one of these fits. He deduced from his work a scale of colour by which a colour was classified by the thickness of the plate which gave rise to it. His great powers of observation were shown in the discovery of what are known as the colours of thick plates, which generally require some finding even when one knows where to look for them. He showed, too, that solar and lunar haloes were due to the presence of minute drops of water all of the same size.

Newton's experiments on thin plates so impressed him with their possibilities for the production of colours that he brought forward a theory of colour in which he supposes that the colours of all natural bodies, even coloured solutions such as wine, arise in this way. He supposes that the smallest particles of bodies are transparent and would be colourless if alone. When, however, they congregate together, as in solids and liquids and to some extent in gases, their parts are separated by interstices, and a rough description of his theory is that the colour of a body is that of a thin plate the thickness of which is equal to the interstice. Newton, though he had an accurate idea of the scale of the structure of light, very much overestimated the coarseness of the structure of matter. He says in his "Optics" that if we could make microscopes to magnify some 5000 times, we could probably detect these interstices. He thought that the interstices were of the same order as the length of a 'fit' of easy transmission or reflection, whereas we know that they are less than 1/1000 of that distance, much too small to be of any use for Newton's theory.

Another ingenious application of the colour of thin plates was his explanation of the blue colour of the sky. He supposes that it is due to minute bubbles of water in the air, and that the bubbles are thin enough to make the blue predominate. This theory lasted until comparatively recently, when the late Lord Rayleigh showed that a quite distinct though in some respects analogous effect, the scattering of light by small particles in the air, gave an explanation more in accordance with the facts.

I now turn to the question of Newton's views as to the nature of light. Newton was always exceedingly careful not to tie himself down to any precise specification of the structure of light. He would not, I think, have accepted as a correct representation of his views the theory that was fathered upon him by his successors, that light consisted of small material particles and nothing else. We have in the letters to Hooke and Boyle a record of the ideas about light which were passing through his mind when he was busiest with his optical researches, and we find that then the ether was an integral part of his conception of light. He says: "Were I to propound an hypothesis it should be this, that light is something capable of exciting vibrations in the ether." He gives, however, his reasons for thinking that there must be something besides these vibrations, and gives a long list of alternatives.

> "They that will may suppose it an aggregate of various peripatetic qualities. Others may suppose it multitudes of unimaginable small and swift corpuscles of various sizes springing from shining bodies. . . . But they that like not this may suppose light any other corporeal emanation, or any impulse or motion of any other medium or etherial spirit diffused through the main body of aether or what else they may imagine proper for their purpose. To avoid dispute and make this hypothesis general, let every man here take his fancy, only whatever light be I suppose it consists of rays differing from one another in contingent circumstances as bigness from vigour."

Again, in his letter referring to Hooke's undulating theory he says: "The hypothesis of light being a body, had I propounded it, has a much greater affinity with the objector's own hypothesis than he seems to be aware of, the vibrations of the aether being as useful and necessary in this as in his."

In the "Optics," published thirty years later, which begins: "My design in this book is not to explain the properties of Light by Hypothesis, but to propose and prove them by reason and experiment," the ether is not introduced into the body of the book. The idea of 'fits' of easy transmission and reflection is sufficient for his purpose; he just postulates the existence of these 'fits,' saying: "I content myself with the bare discovery that the rays of light are by some cause or other alternately disposed to be reflected or refracted through many vicissitudes." But if the ether is banished from the three books of the "Optics" it appears in full vigour in Query 29. Newton says:

> "Are not the rays of light very small bodies emitted from shining substances? Nothing more is requisite for putting the Rays of Light into Fits of easy Reflection and easy Transmission than that they be small bodies which by their attractive power or some other Force, stir up Vibrations in what they act upon, which Vibrations being swifter than the Rays overtake them successively and agitate them so as by turns to increase and decrease their velocities and thereby put them into those Fits."

Thus Newton regarded light as possessing a dual structure, one part of which was the small corpuscle, the other the vibrations which surround it. One very important feature of Newton's theory of light, and one which differentiates it very sharply from the undulatory theory, is that on Newton's theory the structure of light is essentially atomic; it is made up of discrete and definite parts. He says in his first definition, "by the rays of light I understand its least parts." He regards light as made up of those parts which travel through space unchanged; the light coming to us from a star is made up of particles of exactly the same kind as those in the light as the star itself; the only difference is that the particles get more and more widely separated, as the distance from the star increases.

Let me illustrate the difference between this result and that which obtains on the undulatory theory by the consideration of the following case. Suppose we have a battery of guns in action. The guns emit both shot and waves of sound; as we go farther from the guns our chance of being hit by the shot gets smaller, but if we are not so far away that the shot has lost speed, the effect when we are hit is just as bad as if we were nearer to the guns; the effect of increasing the distance is to diminish the number of casualties without changing their character. Now consider the sound waves. Let us call the striking of these waves against our ears a casualty; also when we go to a greater distance the chance of these continuous waves hitting us will be just as great as when we are nearer in, but the noise will fall away quickly as the distance increases. In this case the number of casualties will not diminish with the distance but their character will change. This is a fundamental difference between a corpuscular and an undulatory theory.

In recent years great attention has been paid to the electrical effects produced by light; one of these is the emission of electrons from a metal surface when light falls upon it. The number and velocity of these electrons can be measured with considerable accuracy. It has been found that as the distance of the metal from the source of light increases, the number of electrons emitted decreases; that is, the number of casualties diminishes, but those electrons which are emitted are moving just as fast as when the metal was close to the source of light: that is, the character of the casualties is not changed. This is but one of many of the electrical effects produced by light which show the same characteristic. In fact, all these effects indicate that the structure of light must be atomic rather than continuous. If we confine ourselves to the corpuscles, though we might explain the electrical effects we could not explain the optical phenomena of interference; but we must remember that Newton in his confidential moods never contemplates the corpuscle as being the sole constituent of his units. These were always accompanied by vibrations in the ether, and the effect of these as well as the corpuscles must be taken into account.

At the end of the "Optics" come the Queries. In these Newton abandons the severe, almost Euclidean, style of the earlier part of the book; he flings away his policy of "hypotheses non fingo"; he makes up for lost time. The suggestions he makes are extraordinarily acute and suggestive. Here is one of them.

> "Are not gross bodies and light convertible into one another and may not Bodies receive much of their activity from the particles of Light which enter into their composition. The changing of bodies into Light and Light into Bodies is very conformable to the course of Nature which seems delighted with transmutations."

In another Query Newton connects the abnormal refracting powers of some substances with their chemical nature, a subject which is now of great importance. The connexion he suggests is that since these bodies are so affected by light, their chemical nature is such as to make them readily take fire and emit light for themselves. This is the first and most daring of reciprocal relations of the type we are now familiar with in thermodynamics.

Newton suggests that the ether in itself is atomic and that the atoms may not all be of one size. He calculates from the rise of liquid between two glass plates the force exerted by the attraction of the particles of the glass on water at a distance of $\frac{3}{8}$ of one hundred thousandth part of an inch, that is, about one millionth of a centimetre, and finds it sufficient to hold up a cylinder of water two or three furlongs in length. He has extraordinary clear and definite ideas about chemical combination much in advance of anything which appeared for more than a century afterwards.

I have confined myself to Newton's work on optics. I have not time to do more than recall that he was the first to give the theory of the propagation of waves of sound. His work in physics is but a part, and perhaps not the most important part, of his scientific work, but if it stood alone his would still be one of the great names in science.

Newton's Work in Pure Mathematics.[1]

By Prof. L. J. Mordell, F.R.S.

When we consider the numerous and wonderful developments of mathematics since the beginning of the last century, it is very difficult for us to appreciate the state of mathematics just before the rise of Newton. The period was a critical one in the history of this science. All the signs pointed to a great awakening, and the world was ripe for important and far-reaching discoveries. This was the time of the last days of Fermat (1601–1665) and of Descartes (1596–1650), who had both initiated epoch-making discoveries. From the modern point of view, what little was known related to geometry, trigonometry, algebra, and the theory of equations. Their fundamental principles had been laid down roughly in the form in which they are now familiar to elementary students. General theorems were extremely scarce. Each new differential property of a curve, each new expansion of a function of x, required new methods. Mathematics was chiefly a collection of isolated theorems and examples.

Many distinguished mathematicians have shown unmistakable signs of mathematical genius at an early age. Newton, however, knew no mathematics when he entered Trinity College in 1661 at nineteen years of age. He was introduced to mathematics in his first term by the purchase of a book on astrology, which he could not understand because of the references to geometry and trigonometry. He then started to study Euclid's geometry, which he found very easy and almost obvious. He followed with a book on arithmetic and Descarte's "Géométrie," which was difficult enough to interest him. As an undergraduate he also read the works of Vieta, Van Schooten, and Wallis.

Newton's original investigations were commenced early in his career. In a manuscript of his written in 1665, the year in which he took his B.A. degree, there is the earliest documentary proof of his invention of the fluxional calculus, that is, what is

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