HISTORY OF PHYSICS

by MAX VON LAUE

translated by RALPH OESPER

ACADEMIC PRESS INC., PUBLISHERS
New York 1950

ACADEMIC PRESS INC.

125 East 23rd Street, New York 10, N. Y.

PRINTED IN THE UNITED STATES OF AMERICA

Optics

OPTICS IS NOT MUCH YOUNGER than mechanics. The knowledge of the linear propagation of light and the concept "ray" extend back far into antiquity. The ancients likewise thought about reflection and refraction, and they were acquainted with methods of copying by means of concave mirrors and lenses. The position of the focal point, but also the inexactness of the reunion of the rays in the image of a point of light, were described by Roger Bacon (1214?-1294). Spectacles seem to have been invented around 1299 by Salvino degli Armati, a Florentine. The law concerning the direction of the reflected ray also is one of the oldest heritages of unknown origin. In contrast, the law of refraction can be credited to two men. The first, Willebrord Snell or Snellius (1591-1626), according to the testimony of Huygens, deduced the law from actual measurements and published it in a work that has been lost. The second, René Descartes (1596-1650) derived it from his corpuscular conception of light. Kepler was not quite correct in this matter; his formula holds only as an approximation for small angles of incidence, but it was good enough for him to develop a thoroughly usable theory of the telescope. Nevertheless, the laws of reflection and refraction provided a complete physical foundation for geometric optics, whose further development then came chiefly from mathematicians and instrument makers. Men such as William Rowan Hamilton and Karl Friedrich Gauss (1777-1855) participated but, despite the expenditure of much effort and acumen, the structure is not yet finished. Limits are set to its validity by the wave nature of light; they reveal themselves, in the case of the microscope, by the fact, known in 1874 by Ernst Abbe (1840-1905) and Hermann von

Helmholtz, that with visible light there is no resolution of distances smaller than 10^{-5} cm. Of course, since this limit is less when ultraviolet light, whose wavelength is shorter, is employed, and with X-rays, as has been known since 1912, it is possible even to deal optically with the distances between the atoms of solid bodies. They are of the order of 10^{-8} cm (see Chapter XII).

The explanation of colors presented a particular difficulty to optics in its earliest period. The proof (1672) that white light is composed of light of various colors, and that consequently colored light is simpler in nature than white light, was Isaac Newton's second great accomplishment. Nothing illustrates its importance better than Goethe's vehement protest (1791-92 and 1810) against it, which in the end goes back to the fact that the eye, unlike the ear, which harmonically analyzes the vibrations that are stimulating it, perceives white light as a unit. Newton was led to his studies with the prism by the chromatic error of optical instruments, a defect which he considered unavoidable. His design and construction of the reflecting telescope, which fundamentally steers clear of this fault, was a logical step. His successors also maintained this position, until 1753 when John Dollond (1706-1761) produced an achromatic telescope objective, in which the chromatic aberrations of two varieties of glass were mutually compensated. In 1800, Friedrich Wilhelm Herschel (1738-1822) found that the limits of the spectrum do not coincide with those of its visible region, but, on the contrary, less refrangible radiation, revealed by its heating effect, adjoins the red. The next year, Johann Wilhelm Ritter (1776-1810) and likewise William Hyde Wollaston (1766-1828) discovered the chemically active radiation beyond the violet.

The quantitative study of the continuum of different kinds of light, which the prism separated, presented a problem similar to that of the measurement of time (see Chapter I). The designations red, yellow, etc. were too loose to serve as divisions within this band of light, and they were also too subjective, since they differ from person to person. Hence, it was a great advance, when, in 1814-15, Joseph von Fraunhofer (1787-1826), by introducing a collimator and telescope before and behind a prism, discovered in the solar spectrum the sharp, dark lines which now bear his name. He used them as markers and immediately was able to define closely the measurements of the refractive index by assigning a value of it to each of these lines. This procedure is still used for some technical purposes. However, the problem was not solved until 1821-22, when he discovered diffraction by a grating, and Friedrich Magnus Schwerd (1792-1871) provided (1835) an explanation of it based on the undulatory theory. From then on, it has been possible to coordinate every variety of light with wavelengths, which can be measured with relative accuracies to within 10^{-7} cm from the constants of the grating and the angle of diffraction. This marked the real beginning of spectroscopy which has always had tremendous importance for the entire field of science and technology. For instance, wavelength measurements by F. Paschen (1865-1947) on the lines of hydrogen and helium, and the precise determinations of Rydberg's constant based on these data, became a decisive verification of Bohr's atomic model (Chapter XIV).

Another question that was much discussed in the seventeenth century was: "Does light have a finite velocity?" Descartes denied, and Galilei affirmed, both without experimental basis for their respective opinions. In fact, the laboratory resources of the period were not adequate to deal with this problem. However, in 1676, Olaus Römer (1644-1710), using observations of the almost but not quite periodic eclipses of one of the moons of Jupiter, came to his famous conclusion that the velocity of light in empty space is about 3×10^{10} cm/sec. The aberration observations in 1728 by James Bradley (1693-1762), despite the doubts of the Cartesians, provided the very welcome confirmation that it is 10^4 times greater than the velocity of the earth in its orbit. Laboratory determinations were not made until 1849 when Armand Fizeau (1819-1896) employed a rotating toothed wheel, and in 1862 Jean Bernard Leon Foucault (1819-1868) used a rotating mirror. These measurements were repeated by many, mostly by the same methods. The latest determination was made by Albert Abraham Michelson (1852-1931) in 1925 and 1926. He measured the time required for light to make a round trip between Mount Wilson and Mount Antonio in California, a total distance of 70 kilometers. His result was 2.99796×10^{10} cm/sec, with a probable error of 4×10^{5} cm/sec.

The discovery of interference, diffraction, and polarization became decisive for the theory of light. The earliest of such observations were made by Francesco Maria Grimaldi (1618-1663) who in his posthumous book (1665) gives a detailed description of diffraction at a rod and at a grating. Even after Newton repeated these experiments, they remained without influence on the development. The same is true of the discovery by Robert Boyle of the colored rings exhibited by thin films, which now are called Newton's rings, because the latter was the first to recognize the relation between color and thickness of the layer. Newton accepted a corpuscular "emanation theory" of light, though with some reservation, because he obviously put more weight on his experimental findings than on their elucidation. In the Introduction to his *Optics* he rejects the making of hypotheses just as firmly as at the close of the *Principia.* Nevertheless, his less brilliant successors tenaciously retained this theory, which survived even into the nineteenth century. For instance, it was supported by Jean Baptiste Biot, who was not convinced of the validity of the undulatory theory until quite late, even though he was permitted to witness its growth at close range.

Grimaldi only tentatively, and Hooke more decidedly, had considered a wave theory. However, the latter really dates from the "Traité de la lumière," which Huygens presented to the Paris Académie in 1678, and which appeared in print in 1690. From the assumption of a longitudinal wave motion, he derives, by means of his envelope construction, rectilinear propagation, and the laws of reflection and refraction. The latter was applied not only to isotropic bodies, but also to calcite, whose double refraction he explained as due to the joint action of two wave fronts, of which one is a sphere, as in an isotropic body, and the other a revolution ellipsoid. There is nothing in Huygens' book about the spectral resolution into colors.

In contrast to mechanics, there was practically no progress in the theory of light during the eighteenth century. Then there began the "heroic" period of the undulatory theory, which extended from 1800 to about 1835; the development took place chiefly in England and France. Thomas Young (1773-1829) announced his idea of interference in 1801 and applied it in the familiar manner to Newton's rings. He thus became the first to obtain an approximate measure of wavelengths of light. Furthermore, he recognized the difference between coherent rays, coming from the same light source, and incoherent rays. He employed the idea in explaining diffraction, which he regarded as interference between the light going directly through the diffraction aperture and the boundary waves. This will be discussed later. Polarization was discovered by Etienne Louis Malus (1775-1812) in 1809. He believed it provided a refutation of the undulatory theory; but, actually, it is incompatible with the longitudinal waves of Huygens' "Traité." Thereupon, in 1811, Dominique François Arago (1786-1853) described the color phenomena that can be seen on crystals in polarized white light. As a consequence, Thomas Young found it necessary to declare his belief in the transversality of light waves, even though this idea definitely contradicted the usual views. In 1815, the brilliant Augustin Jean Fresnel (1788-1827) began his all too brief career of discovery. In addition to many new observations on diffraction and interference, he contributed the theory of diffraction in the form of zonal construction, which firmly implanted the Huygens envelope principle in the interference idea. He and Arago in 1819 furnished the proof that polarized rays at right angles to each other do not interfere, a discovery which finally put the theory of tranverse vibrations on a firm footing. His crystallooptics, which is still accepted, explained Arago's experiment, among other things. Finally, Fraunhofer's diffraction studies (1821-22), which deviated from those of Fresnel and were simpler from the theoretical standpoint, came in this same period, which in a sense, was brought to a close by Schwerd in 1835 in his comprehensive work: "The diffraction phenomena analytically developed from the fundamental laws of the undulatory theory."

The idea of interference, that rays on meeting, in contrast to beams of corpuscular particles, do not necessarily strengthen each other, but rather can weaken each other to the point of complete extinction, has since then been one of the most valuable possessions of physics. Whenever the nature of a radiation is in doubt, an effort is made to produce interferences; if successful, the wave character is definitely established.

Light was thus proved to be a transverse wave motion. In the course of time, interference apparatus and experiments increased greatly in proportion to the advance in the art of experimentation, and they, in turn, contributed to greater accuracy of measuring. About 1834, Macedonio Melloni (1798-1854) showed that infrared rays behave as light does in reflection, refraction, and absorption experiments, and in 1846 Karl Hermann Knoblauch (1820-1895) by means of diffraction, interference, and polarization experiments, demonstrated that such radiation differs from light only with respect to its greater wavelengths. The new art of photography was applied to the shorter wavelength ultraviolet radiation. A still greater extension of the knowledge of the spectrum came in November, 1895, when Wilhelm Conrad Röntgen (1845-1923) announced his epoch-making discovery. Almost immediately (1896) it was concluded by Emil Wiechert (1861-1928) and George Gabriel Stokes (1819-1903) that Röntgen rays, judging from the manner in which they are produced, must be a type of radiation with particularly short wavelength. This conclusion was fully confirmed by the polarization studies of C. G. Barklas and the interference investigations by W. Friedrichs and P. Knipping

(1883-1935) on the atomic space lattices of crystals. The wavelengths of X-rays range between 10^{-7} and 10^{-9} cm.

The theory of optics was also making progress. First of all, Young's idea of boundary waves in diffraction received an unexpected substantiation when L. George Gouy (1854-1926) in 1883 and Wilhelm Wien (1864-1928) in 1885 observed them directly in the light deflected at large angles; up to then, the observations had been confined to the immediate vicinity of the shadow boundaries. G. R. Kirchhoff, whose work on the mathematical wave theory was continued by A. Rubinowicz in 1917, put Fresnel's brilliant idea of zone construction on a firm basis in that, for instance, he proved mathematically the identity of the Young and the Fresnel concepts of the diffraction process. All these studies were dependent on approximation methods, but in 1894, A. Sommerfeld successfully dealt with the diffraction by a straight edge in strict mathematical fashion and then went on to show that the previous approximations were justified.

In the beginning, light vibrations were regarded as elastic waves, similar to the transverse oscillations in solid bodies. No other concept was possible at that time. The medium, which was supposed to carry the vibrations through empty space, was called the ether. Ever since E. Torricelli and O. v. Guericke had produced fairly high vacua (see Chapter II), there was no doubt that light, in contrast to sound, needed no material medium for its transmission. Of course, it was then difficult to explain why only transverse, but not also longitudinal waves, occur in the ether; bodies, in which only longitudinal but not transverse waves are possible, were known in the liquids and gases. No elasticity theory could account for the reverse case. Likewise, there was no complete mathematical solution for the problem of reflection and refraction. Then, in 1865 J. Clerk Maxwell (1831-1879), on the basis of his theory of electricity and magnetism (Chapter V), drew the mathematical conclusion of the possibility of electromagnetic waves, which travel with the velocity of light, and immediately he took light as an example. The electromagnetic theory accorded with experience better than the elasticity theory in so far as it permitted only transverse waves, and it relegated the difficulties of presenting the mechanical properties of the ether to the more general problem of a mechanical elucidation of electrodynamics as a whole. Furthermore, Maxwell's theory led to a simple relation, which fitted the empirical findings in many bodies, between the index of refraction and the dielectric constant, and it contained, as was shown in 1875 by Hendrick Antoon Lorentz (1853-1928), the complete theory of the Fresnel intensity formulas for reflection and refraction, which had been verified experimentally but which had not been explained by the theory of elasticity. Despite these advantages, it had to battle for three decades to secure acceptance, because the older theory, supported by the general mechanical conception of nature, was so firmly entrenched. After Heinrich Hertz discovered electromagnetic waves in 1888 and showed that they exhibit all the characteristics of light—refraction, reflection, interference, diffraction, polarization, and also travel with the velocity of light —victory gradually veered to the new theory. The long standing dispute as to whether the light vibrations occur in the plane of polarization, as postulated by Fresnel, or normal to it, as stated by Franz Neumann (1798-1895), was decided by the Lorentz theory of reflection and also by an experiment on stationary light waves made by Otto Heinrich Wiener (1862-1927) in which it was shown that the electrical field intensity vibrates perpendicularly to this plane, the magnetic strength within it. This uncoerced coalescence of the theories of light and electrodynamics, which hitherto had been completely independent, is one, and perhaps the greatest, of those events to which the Introduction referred as proofs of the truth of physical knowledge.

Although Maxwell's original theory gave a complete account of the propagation of light through empty space, it did not cover the optical properties of matter satisfactorily; in particular, it did not explain the dispersion of the refractive index.

The molecular transformation into the "electronic theory," which was due primarily to Joseph Larmor (1857-1942) and H. A. Lorentz, furnished the necessary supplement to the earlier theory. It accounted not only for dispersion, but also for a phenomenon discovered in 1871 by August Kundt (1839-1894), namely, the anomalous dispersion accompanying selective absorption, which it treated as a resonance phenomenon of atomic structures capable of oscillating. This electron theory had its greatest triumph when, by its aid, H. A. Lorentz elucidated the discovery (October, 1896) by Peter Zeeman (1865-1943) that spectral lines can be separated in magnetic fields. Magnetic rotation of the plane of polarization, which had been discovered as early as 1845 by Faraday, is intimately related to the Zeeman effect. There had now been developed a theory which in completeness was not inferior to that of mechanics and which took account of all the phenomena connected with the propagation of light. However, only three years later, it was found inadequate to deal with the facts of absorption and emission of light. These will be discussed in Chapters XIII and XIV.