FUNDAMENTALS
OF
PHYSICAL OPTICS

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PREFACE

This textbook is intended for use in an advanced undergraduate course in optics. The student is assumed to have completed a thorough course in elementary physics and to be familiar with the methods of the calculus. We have presented the material in such a way, however, that the book may be used in classes in which some students do not have the above mathematical preparation. Thus wherever possible the mathematical derivations are supplemented by simple graphical or vector treatments of the problem. The applications of calculus have been purposely made very brief, but are always included for the benefit of those students with a mathematical turn of mind. The main emphasis is placed on the physical explanation of the various phenomena, which we believe is most successfully accomplished in the present subject by the use of graphical methods. For this reason a large number of illustrations have been prepared with considerable care to have them as exact as possible.

We have deliberately restricted the subject matter to rather narrow limits. Thus, on the one hand, we have included no geometrical optics. The knowledge of this subject gained in an elementary physics course is ample for an understanding of the material of this book. On the other hand, no systematic discussion of the quantum theory and its applications to spectra and atomic structure has been given, even though this is an essential part of the subject of physical optics as the term is generally understood. It would have been impossible to include an adequate account of this field without a considerable increase in the size of the book. We have therefore limited ourselves strictly to the so-called classical physical optics or wave optics. This has been necessary in order that there should be room for a sufficiently detailed consideration of our subject.

But there is a more fundamental reason for this limitation than the mere exigencies of space. The complementary character of the wave and quantum aspects of light, which is an essential part of the modern theory, reveals these as two equally important, but quite distinct, fields of study. In covering only the one field, the book achieves a unity which would be lost by the inclusion of a necessarily brief account of the other field. The usual procedure in an introductory presentation of light has been to develop the wave theory first, and afterward to describe some of the quantum phenomena requiring the particle theory. The dilemma in which we are left concerning the true nature of light is then emphasized in such a way as to leave the impression that ultimately one or the other of these theories will prove to be correct. It seems to us that the time has come to adopt the point of view emphasized by the quantum mechanics, namely, that the wave and particle properties of light are merely two different aspects of the same thing, and that one will probably never be more important than the other. These two aspects are to be regarded as complementary rather than as antagonistic. Although the acceptance of this point of view requires a fundamental change in our ideas as to what constitutes an "explanation" of a phenomenon, the thoughtful student should certainly be given the benefit of this newer outlook.

The dual character of the present theory of light and matter leads to a logical way of dividing the subject matter into two parts. On the one hand classical mechanics, the mechanics of particles, corresponds to the quantum picture of light and to geometrical optics. On the other hand the wave mechanics corresponds to wave optics. In confining ourselves to the latter field, we are covering the subject of "physical optics" in the sense of classical physics only. In our opinion the quantum aspects of light, which are apparently so sharply divided from the wave aspects, are best presented in a separate course. If it is desired to include them in the same course, reference should be made to other books in which a fairly complete treatment of the quantum theory is given. To be sure, it was not necessary or desirable to omit all mention of the quantum aspects in the present book. In the later chapters, which deal with the interaction between light and matter, we have been careful to point out the shortcomings of the wave picture, and the necessity of turning to the quantum theory for a complete explanation.

The most beautiful and striking experiments in physics are to be found in the field of physical optics. Hence it is very desirable that as many as possible of these be shown to the class or performed by the students themselves. Descriptions of many demonstration experiments are given throughout the text; these are set off from the text itself by horizontal lines. The laboratory work accompanying the course now given at the University of California is described in "Laboratory Experiments in Physical Optics," by R. S. Minor and H. E. White.

In writing this text we have had free access to the lecture notes used by Professor R. T. Birge in his advanced course on physical optics, and from these we have taken some of the explanations and drawings used in the more involved phases of the subject. We are also deeply indebted to Professor Birge for reading the entire manuscript and for making numerous valuable suggestions in regard to it. We wish to express our sincere thanks to Professor R. S. Minor for the ruling of the various special diffraction gratings used by us in obtaining the photographs in Figs. 6A, 6E, 7A and 7F.

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CHAPTER 1

LIGHT AS A WAVE MOTION

A large class of optical phenomena can be explained by assuming that light consists of waves. Many of these phenomena are not commonly observed in everyday life, but appear, for example, when we make a detailed examination of the effects of passing light through narrow openings or reflecting it from ruled surfaces. Any case of the interaction of two or more light beams with each other can be treated quantitatively by wave theory. Another important class of phenomena requires for its complete explanation the assumption that light consists of small bundles of energy called photons, which are essentially particles of light. In this class, the phenomena always involve the interaction of light with matter. An example is the liberation of electrons from a metal surface by light, called the photoelectric effect. The same two classes are known to exist for material particles. An electron or an atom behaves in some ways as though it were a group of waves. In this book we shall be concerned with the first of the above classes, *i.e.*, that which can be explained in terms of waves. Our conclusions will apply to the waves of material particles as well as to light waves. Hence we begin with the investigation of wave motion in general, indicating as we proceed how the various characteristics of light depend on those of the waves of which we assume it to consist.

1.1. Periodic Motion. Since the passage of a train of waves through a medium sets each particle into periodic motion, we shall first find how to give a quantitative description of this kind of motion. A periodic motion is one which repeats itself exactly in successive equal intervals of time. At the end of each interval, the particle finds itself with the same position and velocity, and the time between such occurrences is called the *period*. The simplest type of periodic motion along a straight line is one in which the displacement y from a fixed center is given by the equation

$$y = r \sin (\omega t + \alpha), \tag{1a}$$

where t is the time and r, ω and α are constants. This is the motion of the projection, N (Fig. 1A) on the y axis of a point P moving with uniform speed in a circle of radius r. If P has the position P_0 when we start counting time, ($t = 0$), and revolves counterclockwise with an angular velocity of ω rad/sec, the projection N will move up and down the y axis with a displacement y ($= ON$) given by Eq. 1a. The maximum value of the displacement is r, which is called the *amplitude* of the motion. The whole angle $(\omega t + \alpha)$ determines the position of N at any instant, and is called the phase angle, or simply the *phase*. The position N_0 at zero time is specified by the angle α, which is the initial value of the phase, or the *phase constant*. The period T is the time for a complete revolution of P. This requires a time $2\pi/\omega$ sec, since 2π is the angle swept out in a complete revolution at the rate of ω rad/sec. The period is also the time for one complete to-and-fro vibration of N along the straight line, and after the time T has elapsed the point N finds itself in the same position and with the same velocity (direction included) as it had at the beginning of this time. The reciprocal of the period is the *frequency*, $\nu = 1/T$ vibrations per second, because the number of vibrations performed in a time of 1 sec. will be this time divided by the time T required for one vibration.

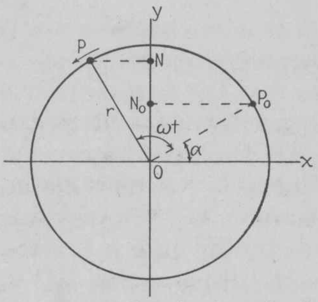

FIG. 1A.—Showing how simple periodic motion may be represented by the projection on a diameter of a point P moving with uniform speed on the circumference of a circle.

The velocity of the point N varies between zero at its extreme end positions, when P crosses the y axis, and a maximum at the center where P crosses the x axis. An equation for the velocity is obtained by differentiating Eq. 1a. At any instant it is given by

$$v = \frac{dy}{dt} = r\omega \cos (\omega t + \alpha), \tag{1b}$$

so that the maximum velocity is $r\omega$ or $2\pi r/T$. The acceleration a is zero at the center and a maximum at the extremes, since by differentiation of Eq. 1*b*,

$$\begin{aligned} a = \frac{dv}{dt} &= -r\omega^2 \sin (\omega t + \alpha) \\ &= -\omega^2 y. \end{aligned} \tag{1c}$$

In the last form, the equation tells us that the acceleration is proportional to the displacement y, since we have assumed ω to be constant. The minus sign indicates that the displacement y is always opposite in direction to the acceleration. Referring to Fig. 1*A*, when N is above O, the acceleration is downward, and when N is below O, it is upward. According to Newton's second law, that force equals mass times acceleration, Eq. 1*c* means that the motion of a mass point will be given by Eq. 1*a* if it is acted on by a force which is proportional to the displacement and in the opposite direction. This type of motion is frequently termed simple harmonic motion or *simple periodic motion* and is physically realized in the vibrations of an elastic medium where the displacements are small and hence the forces are governed by Hooke's law.

Although simple periodic motion is evidently a very specialized type of periodic motion, it is of great importance, not only because it is frequently met with in actual waves, but also because as we shall see any complex type of periodic motion can be represented as the sum of two or more such simple motions with suitable amplitudes, periods, and phase constants (Sec. 2.5). If the more complex motion is in a straight line, the component simple periodic motions from which it is made up will lie also in this line, whereas if it is confined to a plane rather than a line, we may regard it as made up of two motions (usually both complex) along two axes in this plane at right angles to each other. For example, a motion in an elliptical orbit with constant speed may be regarded as made up of two linear motions, one along the major axis and one along the minor axis of the ellipse, neither being simple periodic. If the particle is attracted to the center of the ellipse with a force proportional to the distance between the particle and the center, the speed in the ellipse will not be constant, but the projection along either of the axes of the ellipse or, more generally, along any other straight line through the center, will be a simple periodic motion.

Linear, circular, or elliptical vibrations are the types most frequently dealt with in the study of light waves. The vibrating source, which is necessary for the emission of any kind of waves, may for certain cases of the emission of light be thought of as an electron revolving about the nucleus of an atom. For a large orbit, the force exerted by the rest of the atom on the electron in question will vary approximately as the inverse

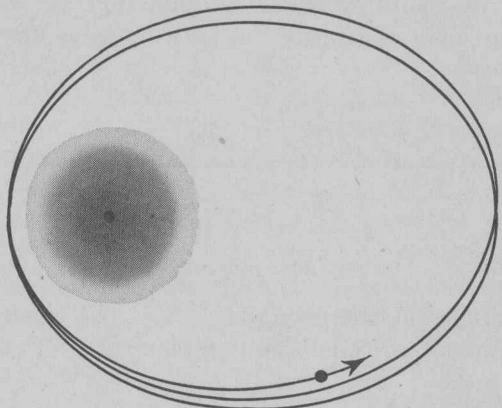

FIG. 1B.—Schematic diagram of a sodium atom with its single orbital electron.

square of the distance (Coulomb's law), and the orbit will be nearly an ellipse with the nucleus of the atom at one focus. The vibrations in the light emitted in a direction perpendicular to the plane of the orbit will then have an elliptical form corresponding to that of the electron orbit, while in the light emitted in the plane of the orbit they will have a linear form, corresponding to the motion seen when the ellipse is viewed edge-on. Figure 1B shows the orbit of an electron in an atom such as sodium.

1.2. Wave Motion. Waves of the type with which we are most familiar, *i.e.*, waves on the surface of water, are of considerable complexity. However, they may serve to illustrate an important feature present in any wave motion. If the waves are traveling in the x direction and the y direction is vertical, an instantaneous picture of the contour of the waves in the x, y plane is given in Fig. 1*C* by the continuous curve. Let this curve be represented by an equation $y = f(x)$. If the wave contour is to move toward $+x$ with a constant velocity v, we must introduce the time t in such a way that as t increases a given ordinate, such as y_1, will, after a time Δt has elapsed, be found at y_1' farther to the right by an amount $\Delta x = v\Delta t$. This is accomplished by writing the equation $y = f(x - vt)$, since we have, at the two times t and $t + \Delta t$,

$$y_1 = f(x - vt)$$
$$y_1' = f\{(x + \Delta x) - v(t + \Delta t)\}.$$

If now we substitute $\Delta x = v\Delta t$, we find that $y_1' = y_1$, and the above requirement is realized. The wave is in the position of

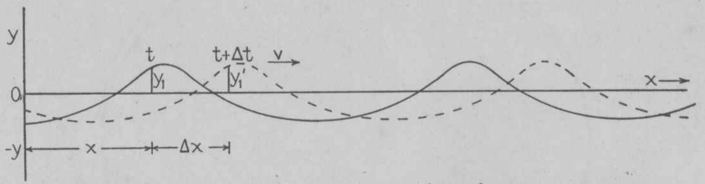

FIG. 1*C*.—Illustrating the propagation of water waves.

the broken curve at the instant $t + \Delta t$. The general equation for any transverse wave motion in a plane is

$$y = f(x \pm vt). \tag{1d}$$

The plus sign is to be used if the wave is to travel to the left, *i.e.*, in the $-x$ direction.

The reader should not infer from the foregoing discussion that the particles of water are transferred to the right along with the wave. On the contrary, the only thing that moves along continuously is the contour, while each particle merely oscillates about its position of equilibrium. For water waves the motion of each particle is circular or elliptical in the x, y plane. In this case the ordinate y is merely the y component of the displacement of the particle from its equilibrium position, since the motion is not a transverse one confined to the y direction. Hence we next consider the simplest type of waves, where this complication does not arise.

1.3. Simple Periodic Waves. Suppose that the wave contour $y = f(x)$ is given by