PHYSICAL PHENOMENA AS INTERPRETED IN RECENT TIMES*

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Introductory

A change in the outlook of physicists and in the associated physical theory began, rather gradually, as the end of last century approached. This had its origin in the unsuccessful efforts of the natural philosophers of that time to account satisfactorily for certain well-authenticated phenomena in terms of the accepted physical theory, which of course was based on Sir Isaac Newton's mechanical principles. One formidable problem emerged from the fact that the interpretation of stellar aberration, on the one hand, and of the result of the experiments of Michelson and Morley (1887) on the other, led to conflicting conclusions about the motion of the luminiferous medium relatively to the earth. Another, different, problem was that presented by the experimentally determined distribution of energy in the normal spectrum (spectrum of black body radiation).

The modern theory, which has grown under the impact of these and later problems, has two aspects: (i) a considerable expansion and elaboration of those relativistic features which are prominent in classical Newtonian theory and (ii) quantum theory (quantum mechanics). It is not sufficiently appreciated that both of these have grown out of the classical mechanics of Newton. The special theory of relativity and also wave mechanics are clearly foreshadowed in the remarkable analogy between geometrical optics and mechanics which was made use of by Sir William Hamilton. Foolishly exaggerated and rhapsodical effusions, more especially about Einsteinian relativity, indicate how imperfectly it is understood even by many present-day physicists. In Professor Philipp Frank's book [1] about Einstein we read on page 157—concerning relativity—" It bursts asunder the entire framework within which Newton attempted to comprehend all phenomena of motion " and so on. Professor J. D.

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Bernal writes [2]: "The physical world of Newton and Maxwell has been completely overturned in favour of relativity and quantum mechanics, which still remain half understood and paradoxical theories." Greatly as the present writer admires Einstein and his relativistic theory, he has no hesitation in stigmatising these outbursts as pure nonsense.

What is of course quite true is that Newtonian mechanical theory is inadequate to deal with very small things such as atoms. It also fails to some extent when applied to very large systems, or to extremes generally—one thinks of very high speeds, for instance—but between these extremes is a wide region where it is difficult to estimate, or even to detect, any shortcomings of the old mechanics. The motion of Mercury's perihelion—after allowance has been made for the influence of the other planets—is not accounted for by Newtonian mechanical principles, but is, one might say, perfectly dealt with by Einstein's general theory of relativity; but one finds it rather difficult to think of the physical theory of Newton as "completely overturned" when one remembers that the discrepancy just mentioned, about Mercury, is in fact so minute that 8700 years, approximately, would have to pass before it could increase by 1°! As Bertrand Russell writes [3]: "Einstein's theory involves only very minute corrections of Newtonian results."

Newton's mechanics is the tap root out of which the physical theory of the present day has grown, and it is undoubtedly a limiting case of quantum mechanics from the small-scale side and of general relativity from the large-scale side. Indeed the study of Hamilton's form of Newtonian theory, and his use of the analogy, already referred to, suggest quite clearly not only Minkowski's form of relativity but also *wave mechanics*. The old theory is dominated by a restricted form of the principle of relativity, which Einstein has called Galilean relativity. Newton and his successors were conscious of this; but it seemed so obvious that it was seldom or never explicitly mentioned, and of course the term "relativity" was not yet in use in this sense. Paradoxical though it may seem to many readers, this awareness found its expression in the assumption of an absolute space and absolute time, as will be explained later.

As for Maxwell's electromagnetic theory, it is the precise embodiment of the Lorentz transformation, the nature of which will be indicated below, in the form which Einstein gave it. In other words, Maxwell's theory *implies* Einstein's special relativity theory, and it was the guidance of Maxwell's theory which helped to lead

Lorentz and, still earlier, Voigt to what is now called the Lorentz transformation.*

The Meaning of Relativity

A good illustration is provided by a boat which is being rowed down a stream. We may measure its speed by determining (in one way or another) the rate at which it passes, or leaves, some point on the bank of the stream. In this connection we call the bank the *system of reference.* But we might measure the speed of the boat by determining the rate at which it leaves a raft which is floating in the stream, behind the boat. The two speeds are obviously different. They are in fact referred to different *systems of reference.* It is now appreciated that the measured values of many other physical quantities, besides velocities, depend on the system of reference which is used.

Certain reference systems are, in important respects, much simpler than others. They are called *inertial systems* [4]. Such a system is what we have in mind when we state Newton's first law of motion in the usual way. Now, the laws of Newton's mechanics, including the first law, or the equations which describe them, have precisely the same form *in all inertial reference systems.* This is the *Newtonian principle of relativity*—called by Einstein the Galilean principle of relativity. From Newton's point of view a system which was *at rest* in his absolute space, or any system with a constant velocity of translation relative to his absolute space, was a system of the kind we now call an inertial system. His laws of motion, as he knew, have the same form in all such systems. We have had to give up his notion of absolute space, because it is not associated with any observational significance—we cannot, in fact, determine the velocity of anything *relatively to his absolute space*—but we can determine, or specify, an inertial system with any desired approximation to precision. Not only is there no absolute space—in Newton's sense—but we do not need it, and it is in fact impossible to define it in physical terms. Carl Neumann's Body Alpha (1869) [5] was an advance on Newton's absolute space, because he gave it an observational significance. When we change from one reference system to another—for the moment we have Newton's mechanics in mind—we can very easily calculate the value of a measured quantity in the new system, if we know what it is when referred to the old one and make use of the data which

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* They did not *quite* reach the correct form of the transformation, though Voigt's form of it differs from the correct one, as given by Einstein in 1905, in a quite trivial way.

define the new system. For instance, if we know the speed of the boat, referred to the bank of the stream (first reference system) and that of the raft (second reference system) referred to the bank, we can easily calculate the speed of the boat relatively to the raft. It is a simple exercise in subtraction. This illustrates what is meant by a *transformation* from one system to another, as the term is used in relativity theory.*

Various difficulties, some of which have been mentioned, forced the physicists to a more sophisticated form of relativity, which Einstein later called *special relativity*. It is characterised by a more complicated transformation than the simple Newtonian one—the *Lorentz transformation*. One important reason for this was that the phenomenon of stellar aberration could, seemingly, only be reconciled with the result of the experiments of Michelson and Morley if it were assumed that the lengths of bodies, and of the time intervals between events, changed in general on passing from one inertial reference system to another (Lorentz and FitzGerald). Maxwell's electrodynamical theory, amply confirmed experimentally, also indicated the Lorentz transformation.

Though Lorentz arrived at a set of equations (the transformation named after him), which in fact constitutes the special theory of relativity, he failed to understand its full significance.† This was partly due to his firm belief in the reality of the luminiferous medium (æther). Such a conviction brings one up against the formidable difficulty that no velocity can be assigned to it, whether relatively to the earth or to any other reference system. The fact is that the Lorentz transformation is incompatible with the existence of a luminiferous medium, while at the same time this latter seemed to be demanded by the wave character of light and electromagnetic radiation.

Albert Einstein (1879–) approached the problems we have been discussing about 1904. There is, one feels, no doubt that he was, at that time, strongly influenced by the outlook of Ernst Mach, a famous Viennese philosopher and physicist and, no doubt, the spiritual father of what is now called the Vienna Circle. Einstein simply *ignored* the æther and arrived at what we believe to be the precisely correct form of the Lorentz transformation, which Lorentz

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* Strictly speaking, the term transformation is used for the change we have to make in the numerical specification of positions and times, *i.e.* instants.

† In the obituary notice of Hendrik Antoon Lorentz in *The Times* of February 6, 1928, we read, concerning some of his publications, that "They embodied the first systematic appearance of the electrodynamic principle of relativity." Actually the term "electrodynamic" unduly restricts the scope of the principle.

did *not quite* reach. He understood its significance much better than did Lorentz. We are not referring here to something which seems to have hypnotised the philosophers of science ever since—namely his discussion of simultaneity. The fact that two events may be simultaneous when referred to one system and not simultaneous when referred to another stares us in the face in the later work of Lorentz. The whole of Einstein's paper [6] is based on the results of physical observations and on the expansion, which they suggest, of the old Newtonian relativity, namely, as he explicitly states :

(i) The result of the experiments of Michelson and Morley, and
(ii) The assumption that, not only the laws of mechanics, but also those of Maxwellian electrodynamics (including optics) have the same form in all inertial systems.

The latter assumption he called the *Principle of Relativity*—later the special principle of relativity, to distinguish it from the more general principle formulated some ten years later. Even Einstein—the present writer thinks—did not, at that time, grasp the full import of the Lorentz transformation. It is an inevitable inference from it that space and time constitute a single continuum—the time being its fourth dimension. It may be remarked, parenthetically, that the time traveller, in H. G. Wells's story, *The Time Machine*, *infers* that space and time constitute a single four-dimensional continuum. The Lorentz transformation is simply unintelligible so long as we regard space and time as separate or disconnected continua. It was Hermann Minkowski who established relativity on the foundation of a four-dimensional space-time continuum (1908) and his contribution to it was one of the greatest.

Minkowski's form of relativity makes it easy to understand why the lengths of rods and of time intervals generally change with the change of reference system. The reason is simply that they are analogous to the *components* of, for example, a displacement in Euclidean space [4]. No *actual* change occurs in a physical system merely in consequence of changing the system to which it is referred.

A remarkable and important consequence of the special theory of relativity is the obliteration of the distinction between *mass* and *energy*, the significance of which will appear more clearly when we get into contact with the quantum theory.

The special theory of relativity, while it solved some formidable problems, raised a very difficult new one—that of the wave character of light and electromagnetic radiation and of a luminiferous medium to which no determinate velocity, relative to the earth, could be assigned. We shall indicate later how this problem has been solved.

Einstein's great achievement was, of course, the *general* theory of relativity (*ca.* 1915), which elucidated the hitherto mysterious phenomenon of gravitation. His great stroke of genius was the appreciation that gravitational forces are of the same nature as those which appear, or are modified, or—it may be—eliminated, when we change from one reference system to another *and do not confine ourselves to inertial systems.* This he called the *principle of equivalence.* It is easy to illustrate it. Freely falling things within, or in the near neighbourhood of, a freely falling lift—let us ignore the resistance of the air—if referred to the lift as a reference system, move exactly in accordance with Newton's first law—for a very short time of course. The general principle of relativity is in fact a generalisation—though a very considerable one—of *Newton's first law of motion.*

In order to apply his general principle, which gives the laws (or equations) of physics the *same form in any system of reference* that can be defined, Einstein had to pass beyond the space-time of Minkowski, the geometry of which is like that of Euclid, and assume for his more general kind of space-time the type of geometry called Riemannian, after Bernhard Riemann (1826–66), one of the greatest of German mathematicians.

The results which emerged from his gravitational theory differ from those of Newtonian theory only very, very slightly, as we have seen, for example, in the motion of the planet Mercury. Einstein also made some remarkable predictions—only one of which will be mentioned here. Light from a very distant point (star) which passes close to the sun's limb, according to both Newtonian and Einsteinian theory, is slightly refracted; but while Einstein deduces an angle of $1\frac{3}{4}''$ for this refraction, Newtonian theory leads to just one-half of this. Einstein's prediction was triumphantly confirmed by the observations taken at Sobral (Brazil) and Principe (off the west coast of Africa) during the total solar eclipse on May 29, 1919.

We must pass over recent efforts to expand relativistic theory still further and turn to the other formidable problem which bothered the natural philosophers at the close of last century.

PLANCK'S THEORY

This was presented by black body radiation (full radiation), the radiation filling an exhausted cavity, the wall of which is maintained at a constant uniform temperature—an exhausted furnace, for example. The great difficulty about this black body radiation was that of accounting for the way in which the energy of the radiation is distributed among the different wave-lengths. Newtonian principles indeed *solved the problem for sufficiently long wave-lengths* (at a given temperature); but failed for shorter wave-lengths. Planck solved it completely—about December 1900—by assuming that the emission, or absorption, of radiation, in the form of light or electromagnetic waves, occurred in a discontinuous way. Each sudden discontinuous emission (or absorption) represented an amount of energy equal to $h\nu$, where ν means the frequency of vibration in the light or radiation emitted (or absorbed) and h was a strange new universal constant, which Planck called the *elementary quantum of action*—hence the name *quantum theory*. The constant, h, is exceedingly minute. In C.G.S. units it amounts to $6{\cdot}62 \times 10^{-27}$, which means 6·62 divided by 10 twenty-seven times in succession. This explains why quantum mechanics coalesces with Newtonian mechanics when applied to things as large, shall we say, as those we are constantly handling in everyday life.

Although Planck's theory solved the distribution problem of black body radiation, it will be seen that it made the problem of the wave nature of radiation and of the luminiferous medium more difficult than ever.

One last problem may be briefly described. It arose in connection with the photo-electric effect. This is the name for the phenomenon of the emission of negative electricity—in the form of the small charged particles called *electrons*—from metallic plates when they are irradiated by X-rays, or by light of sufficiently short wave-length. The German physicist, P. Lenard, afterwards one of Hitler's most fanatical supporters, noticed about 1902 that the violence (energy) with which the electrons are ejected was independent of the intensity of the exciting radiation. This was confirmed by A. L. Hughes and R. A. Millikan in the U.S.A. They found that the energy with which electrons are ejected depends *only* on the frequency, ν, of the exciting radiation. Assuming the light or X-rays to be a wave propagation—and they have all the characteristics of waves—the energy is uniformly spread over the plate and when it (the energy) is very small—low intensity—it would seem that the radiant energy in the neighbourhood where an electron is actually emitted should be quite insufficient even to drag it out of the metal. This was the difficulty.

Einstein approached the problem in characteristic fashion. He assumed the light or radiation to consist of small bundles of energy, each containing a quantity of energy equal to $h\nu$, as indeed is suggested by Planck's theory. In fact, he assumed for light (and electromagnetic radiation generally) a *corpuscular* constitution and his theory accounted *perfectly* for all the features of the photo-electric phenomenon.

The identity of mass and energy, which emerged from the expansion of the principle of relativity, endowed Einstein's bundles (we now call them *photons*) with mass and momentum—with very important consequences in the subsequent development of quantum mechanics. The American physicist A. H. Compton predicted a new phenomenon—the Compton effect—by dealing with photons as *if they were particles* with mass and momentum and studying the consequences of collisions between them and electrons. We cannot deal with that in detail here. The prediction of the Compton effect was observationally justified by Compton himself and it had indeed (unknown to him) been observed many years earlier by C. G. Barkla.

The old difficulty, it will be realised, had become more acute than ever before. From the point of view of the photo-electric and the Compton phenomena we cannot escape the conclusion that light is corpuscular. Relativity theory too seemed to have no place for a luminiferous medium; but the phenomena of interference and diffraction seemed to make it certain that light is *undulatory* in character and an important part of the training of students of physics to-day is in the measurement of optical *wave-lengths*!

QUANTUM MECHANICS

About 1924 Prince Louis de Broglie made a suggestion which eventually led to what the present writer thinks is the solution of these problems. His view was that light and electromagnetic radiation consist of *both* waves and particles (Einstein's bundles of energy—photons). The energy of a beam of light he supposed to be carried by the photons or particles, each carrying the quantity $h\nu$, while the function of the waves was to guide the particles. One of de Broglie's most brilliant anticipations was that *all* elementary particles, including electrons, are associated with waves, and he showed how the wave-length was related to, or could be calculated from, the momentum of the electrons. These predictions were completely confirmed by Sir George Thomson, then in Aberdeen, and by Davisson and Germer in the U.S.A. Thus arose *wave-mechanics*—one of the forms of quantum mechanics.

Wave mechanics was greatly expanded by Erwin Schrödinger, who consciously used and expanded the old analogy, which Sir William Hamilton discovered, between geometrical optics and the old mechanics. In fact we have wave mechanics when we lay down that mechanics shall be analogous to optics in the widest sense of the term optics [7]. The correct way to interpret it would seem to be to regard the particles *—in a beam of light, or of electrons, etc.—as the physical entities. They are indeed things which are, in a real sense, observed. The "waves" are expressions of probabilities. When a marksman fires bullets at a target, it is impossible to know where an individual bullet is going to arrive. If, however, he fires thousands of bullets (and we assume he is not allowed to get fatigued) they will be found to be distributed over the target in a way which is described by a well-known mathematical formula. This formula, in fact, expresses the probability that a particular bullet will arrive at a specified small area on the target and probabilities approach certainties when sufficiently large numbers are involved : it is on this fact that the methods of insurance companies are based.

Wave mechanics has a statistical character, and the probability formula involved in it has the same form as that which describes a wave. We can understand therefore that a beam of small particles (electrons or photons) will simulate a wave almost perfectly when a sufficiently large number of the particles is involved.

THE UNCERTAINTY RELATIONS AND CAUSALITY

In earlier statistical theory—*e.g.* in the kinetic theory of gases and Willard Gibbs' statistical mechanics—the statistical laws rested on a foundation, as it were, of *causal* laws ; but the puritan group (the vast majority) of quantum theorists insist that fundamental causal laws are incompatible with those of quantum mechanics. It appears to the present writer that this conclusion can only be adopted when we ascribe an unrestricted validity to certain quantum mechanical statements, *e.g.* to Heisenberg's uncertainty relations (rather improperly called the uncertainty *principle*). For example, the product of the uncertainty in the measured value of a positional co-ordinate of a particle at a certain instant of time and that of the corresponding component of its momentum must be of the order of magnitude of Planck's h at least. If therefore we were to succeed in measuring one of them with extreme precision, the uncertainty about the value of the other quantity would be enormous. This is perfectly true, of course, when our actual knowledge is confined

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* Wave mechanics applies, of course, not only to particles, but to physical systems in general.

to observations made on the system (particle) at a particular instant of time, when of course a precise knowledge of the position of a particle means that the " wave packet " representing it is very minute and is therefore necessarily a superposition of waves of an enormous variety of wave-lengths, and our knowledge of its momentum amounts to no more than is contained in the statement that it is equal to *one* of an enormous number of very different possible momenta.

If, however, we make (legitimate) inferences from the results of observations made on a system (or particle) at *different* times and places, we can indeed determine *both* the position and the momentum of the particle at some precise instant of time with unrestrictedly small uncertainties. The simplest instance is provided by photons. A flash of light is produced at some precisely defined place and instant. Now we know, with an uncertainty which may be reduced indefinitely, that a photon, or photons, will be in some region, whose dimensions may be made indefinitely small, at a precise subsequent instant—*i.e.* the uncertainty of position at this instant may be as minute as we please to make it. But nobody will venture to say that we cannot know its momentum, with unlimited precision, at this instant.

Reflections like these should give us pause before we jump to the conclusion that there is *no causality* in the physical world, and this is reinforced by the fact, admitted even by the puritan quantum theorists, that the " waves " of wave mechanics are subject to well-defined causal laws.

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