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Introduction

> For all practical purposes the wave theory of light is a certainty.[1]

This is the story of a radical change in humans' concept of light. In 1896 most physicists were convinced that light consisted of wave disturbances in a medium, the electromagnetic aether. The energy transported in radiation was thought to propagate spherically outward from its source and to spread out over successively larger volumes in space. Thirty years later, a remarkably different concept of light prevailed. Physicists then took seriously the evidence collected over the preceding two decades showing that the energy of radiation does not spread in space. Under certain conditions, light behaves like a stream of particles.

Our subject is more than the story of a shift from one theoretical explanation of radiation to another. This reconsideration of the nature of light was a significant event in our scientific understanding of the world. To resolve the paradox that faced them, physicists rejected the venerable Platonic dictum that the microscopic realm recapitulates the macroscopic; that laws generalized from the behavior of objects in the perceivable world may be applied to the imperceivable one. By 1927 physicists had assigned to all forms of radiation a curious amalgam of wave and particle behavior. Waves spread energy over larger and larger volumes of space; particles do not. Reconciliation of these conflicting properties was possible only through appeal to an ontology that transcended mechanical incompatibility.

Nature was declared to be only imperfectly rationalizable in terms of human experience with macroscopic interactions. The programmatic goal formulated in the seventeenth century to re-

[1] Hertz, GDNA *Tageblatt* (1890), 144.

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duce all physical phenomena to consistent mechanical representations was here recognized to be unattainable. This was realized in part because of paradoxes found in the behavior of radiation, particularly x-rays. This study is therefore intended to clarify the developing understanding of x-rays and related phenomena early in the twentieth century. But it is physicists' growing awareness that electromechanical explanations of radiation would not work in principle that forms the real subject of this book.

STRUCTURE OF THE ARGUMENT

In the earliest period of our concern, analogies were drawn between known properties of light and the growing empirical evidence about new forms of radiation. Shortly after the discovery of x-rays, it was proposed that the new rays were impulses, not periodic waves, propagating in the aether. Empirical corroboration followed, matched by increasing acceptance; 1907 marks the high-water mark of the pulse hypothesis. Contemporary studies on radioactivity contributed a new example of an electromagnetic impulse: When the properties of the γ-rays were closely investigated, they came increasingly to be explained in the same way as were x-rays. X-rays were the spherically propagating impulses due to the deceleration of cathode-ray electrons; γ-rays were the spherically propagating impulses caused by β-ray electrons accelerating from a disintegrating atom.

The second period brought the first clear attempts to formulate a consistent theoretical picture of the process of ionization by x-rays and γ-rays. Problems were soon recognized when seemingly contradictory aspects of x-ray behavior were discovered. Increasing discussion threw doubt on the validity of *any* electromagnetic explanation of x-rays. J. J. Thomson and W. H. Bragg in England, and Wilhelm Wien and Johannes Stark in Germany, each abandoned critical aspects of the impulse hypothesis. The energy that x-rays pass on to atoms was more than could be expected from any spreading impulse. Moreover, only a few atoms passed over by x-rays emitted an electron; and some physicists asked whether the energy of x-radiation was not propagated only into narrow solid angles centered on the source.

The paradoxical behavior of x-rays provoked two different kinds of investigations in the third period. There were experimental studies of x-rays, light, and γ-rays to determine the angular extent of the effective region that acts on individual atoms. The results indicated that the radiations do not propagate their energy isotropically, but instead concentrate it in a cone of limited extent. At the same time, theoretical attempts were made to explain the restricted solid angle in a way that was compatible with electromagnetic theory. The strongest defender of impulse x-rays was Arnold Sommerfeld, who found explanations for some of the difficulties. But Sommerfeld managed this only by stretching the impulse model to extremes, and by 1912 other problems had arisen. It had become clear that x-rays and light are common forms of radiation; consequently, the paradoxes that plagued x-rays applied just as forcefully to ordinary light. The photoelectric effect in particular became a serious problem after 1911, and several unsuccessful attempts were made to find a classical explanation for it. The basic question was: How can periodic light waves apparently concentrate their entire quantity, or quantum, of energy on an individual electron? Sommerfeld had no answer.

The fourth period began with a new discovery that seemed to corroborate both sides in the debates of the preceding years. In 1912 it was found that x-rays can interfere. On the one hand, x-ray spectroscopy provided unquestionable evidence that some x-rays possess a periodic structure and are therefore no different from ordinary light. X-rays from a given metal produce a characteristic pattern of lines in the spectroscope that is entirely equivalent to optical emission spectra. On the other hand, the new spectroscopy supplied precisely the tool needed to confirm the suspicion that x-rays transfer energy to matter only in discrete units. The quantity of energy that they pass to an electron was found to be roughly equivalent to the total quantum of energy in the radiation. This seemed to leave no alternative but to accept the fact that radiation concentrates its energy in specific directions and does not spread that energy to any extent in space. The same techniques that by 1914 showed x-rays and γ-rays to be bona fide waves soon provided the strongest evidence that they, and ordinary light as well, consist of streams of hypothetical *lightquanta,* localized particle-like concentrations of energy in proportion to frequency or impulse width.

The evidence corroborating the failure in principle of a classical representation of radiation had only begun to appear when Niels

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Bohr proposed his quantum theory of the atom. The lightquantum hypothesis then won almost no support among those whose major goal was the construction of an internally consistent mathematical representation of nature. Throughout most of the decade 1911–21, mathematical physicists simply avoided the issues that complicated understanding of free radiation. The Bohr theory of the atom provided a promising field of investigation that diverted attention from the paradoxes of radiation. During World War I, interest in these problems was maintained almost exclusively by empiricists, those whose views were derived from experiments on the absorption of radiation. Some of these physicists accepted the lightquantum as a valuable heuristic concept before 1920, but none of them inquired deeply into the structure of radiation itself.

The fifth period began in 1921 when influential members of this small group of empirical physicists began to call for a serious reconsideration of the problematic status of light. They based their concern on the successful corroboration of the quantum relation for the x-ray and γ-ray photoelectric effects. In an environment of increasing acceptance of Einstein's lightquantum, two compelling results were achieved. First, in 1922 Arthur Compton showed that x-rays conserve linear momentum in their interaction with electrons. Were the quantum nature of x-rays assumed, remarkable harmony could be brought to the assembled experimental evidence about such interactions. Second, in 1923 Louis de Broglie forged a connection between the properties of light and those of atoms. Each was to have both wave and particle characteristics; only through the interaction of both properties could the true behavior of either matter or radiation be demonstrated. The final reconciliation of the problems of radiation occurred through appeal to indeterministic theories. Soon thereafter, powerful mathematical techniques were applied by Schrödinger and others to provide a full quantum-mechanical solution to problems with both radiation theory and atomic theory.

The polarization between mathematical and empirical approaches to problems about the nature of free radiation ended at just the time that the quantum theory of the atom confronted equally serious problems. Two separate strains of thought, one concerned with atoms and the other with light, were reunited after a decade of unprofitable isolation. It is no coincidence that this recombination of matter theory and radiation theory produced two essentially independent formulations of the new quantum mechanics. One was addressed to the problems of the atom; the other was a development from ideas already formulated to interpret the absorption of light.

BRITISH MECHANISTIC PHYSICS

Most British physicists in the late nineteenth century interpreted nature as if the laws of ordinary mechanics were valid on the microscopic level. Many thought that the electromagnetic aether could be represented in terms of mechanical models. Their approach was based on the conviction that the laws governing the interaction of perceived objects could be transferred bodily to the actions of molecules and atoms. For some, like Maxwell, this was no slavish dependence on physical models, but rather a conviction that, however accurate the mathematical representation of nature might be, the creative impulses of physicists are best served by an appeal to mechanical representations.[2] The British proclivity to seek mechanical models in physics played an essential role in the early recognition that an electromechanical representation is inherently impossible for light.

For our purposes, the most significant example of this attitude in British physics concerns the study of electric discharges through vacuum. It had been known since midcentury that reproducible displays of light and shadow accompany the discharge of electricity through a tube partially evacuated of air. After the improvement of vacuum pumps in the 1860s, it was possible to study the effects of the discharge after most of the gas had been removed and the normal discharge pattern had entirely disappeared. Under these conditions, some sort of disturbance still traverses the tube. Although the responsible "rays" themselves are invisible, they create a bright glow where they strike the glass walls of the discharge tube. Because they seem to come exclusively from the negative electrode, or cathode, they were called *cathode rays*.[3]

One should not be misled by the denotation "rays." To most British physicists, cathode rays were a stream of "charged material molecules." This interpretation had been offered first by William

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[2] Kargon, *JHI*, *30* (1969), 423–36.

[3] Cathode rays were discovered by Plücker, *AP*, *103* (1858), 88–106; named by Goldstein, Berlin *Mb* (1888), 82–124.

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Crookes in 1879 after he showed that the beam is deflected by a magnet, can exert force on an object placed within the tube, and casts sharply defined shadows even when the emitting cathode surface is quite large.[4] The last observation argued against the contention that the rays are emitted isotropically from the cathode, as light would be. There were variations on this theme: Some thought that the particles were complete molecules that had accumulated a net charge; others thought they were the negatively charged products of molecular dissociation. But the majority of British physicists agreed that the cathode rays were material.

Significant research was based on this interpretation. Crookes claimed that he had discovered a "fourth state of matter" that was neither solid, liquid, nor gas because of the extremely low density of the particles. In 1884 Arthur Schuster used the magnetic deviation of the cathode beam to estimate the ratio of charge to mass (e/m) of the presumed particles.[5] As is well known, Joseph John Thomson soon found this ratio to be the same for the beam regardless of the nature of the emitting cathode and the residual gas in the tube. The value of e/m that he found was larger by a factor of a thousand than that of the smallest known atom, and Thomson claimed in 1897 that the cathode beam particles are parts of atoms previously undetected.[6] Thomson's particle is today called the *electron*.

Of most significance in this investigation is Thomson's and Schuster's conviction that the laws of electrostatic deflection, derived from the behavior of macroscopic objects, should necessarily apply to electrons. They were rewarded in this belief by the discovery of new phenomena. Very soon thereafter, Thomson, in particular, encountered perplexing inconsistencies when he tried to apply the same representational standards to the behavior of radiation.

THE ELECTROMAGNETIC WORLD VIEW

Many German physicists regarded the mechanistic bias of British physicists as superficial and potentially misleading. They considered the dependence on mechanical models to be a limitation on

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[4] Crookes, *PTRS, 170* (1879), 135–64. Crookes' lecture "On radiant matter" to the BAAS does not appear in the 1879 *Report* but was reprinted privately the same year.

[5] Schuster, *PRS, 57* (1890), 526–59.

[6] Thomson, *PM, 44* (1897), 293–316. See also Topper, *AHES, 7* (1971) 393–410.

the mind rather than an aid to creative thought. The origin of this deeply ingrained cultural tendency in German physics has not been fully explained. One source of influence is assuredly the prevalent atmosphere of idealistic philosophy to which most turn-of-the-century German-speaking physicists were introduced in their formative or university education. Also, a more abstract interpretation of natural law was common in German-speaking countries, one that placed less emphasis on material interpretation of phenomena than was true in Britain.

In part because of this predisposition, German physicists did not accept British theories about cathode rays. Most of them described the rays as a form of light that traverses the tube.[7] The earliest justification for this view was the belief that only light could stimulate fluorescence in matter like that of the discharge tube walls. The magnetic deflection of the beam could be attributed to an abrupt alteration of the refractive index in the residual gas near the magnet. Heinrich Hertz provided the strongest evidence for the German view in 1883 when he was unable to deflect the cathode-ray beam in an electrostatic potential. He also demonstrated that the beam travels straight ahead even if the course of the electrical discharge curves to the side.[8]

There were therefore very good experimental reasons for German physicists to accept the radiant interpretation of cathode rays. Philipp Lenard, for example, based a Nobel-prize-winning series of researches on the aetherial view of cathode rays. He exploited the fact that the rays could pass right through thin metal foils.[9] This too supported the aetherial explanation; solid matter stops streams of molecules, but some forms of matter are transparent to visible or electric waves. Even after Thomson identified the electron by measuring its e/m ratio, some German physicists – both experimentalists and mathematical theorists – persisted in attempts to explain its behavior entirely in terms of the aether.

German mathematical physicists were not deterred by an inability to represent physical concepts mechanically. A school of thought at this time in German-speaking countries sought to reformulate ideas of matter solely in terms of forces in the aether.[10]

[7] Lehmann, *Lichterscheinungen* (1898), 518–47.
[8] Hertz, *AP, 19* (1883), 782–816.
[9] Lenard, *AP, 51* (1894), 225–68.
[10] On continental rejection of mechanical models, see Klein, *Centaurus, 17* (1972), 58–82. Joseph Larmor in Britain held views similar to those of many Germans; see his *Aether and matter* (1900).

It was a form of electromagnetic reductionism and was heavily influenced by Kantian principles of epistemology. In a famous talk "On the relations between light and electricity" in 1889, Heinrich Hertz conjured up a vision of this way of thinking. Like the pre-Socratic monists who attempted to find the single principle underlying all apparent phenomena, Hertz claimed that physicists were confronted with the question of "whether everything that is, is fashioned from the aether." The aether offers understanding not only of the imponderables, he said, "but even of the nature of matter itself and its most intimate properties, weight and mass."[11] The forces that define our perception of mass and solidity were to be given higher ontological significance than was the idea of matter.

Not all German-influenced physicists agreed with the fullest formulation of this viewpoint. By the mid-1890s, some success had attended a modified version of the reductionist program. This was the electron theory of the eminent Dutch physicist H. A. Lorentz.[12] According to Lorentz, all interaction between matter and the aether is mediated solely by then-hypothetical electrons. Electrons act like particles, but their mass and momentum are only reflections of the effect that a center of electric force has on the continuum of force that constitutes the aether. The mechanical properties of electrons are due to the reaction between their inherent charge and the surrounding electric and magnetic field. Lorentz' detailed theory was able to account for several perplexing observations, including the failure of interference experiments to find evidence for the relative motion of the earth and the aether.

But other physicists interpreted the issues Hertz raised in an extreme form. Some felt that they stood "on the threshold of a new epoch in physics," one in which suitably defined discontinuities in the continuous electromagnetic field would entirely replace mechanical concepts.[13] Emil Wiechert and Wilhelm Wien, for example, felt that the very concept of electron could be reduced to the idea of a form or structure in the electromagnetic medium.[14] Those who subscribed to this all-encompassing reductionist program

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[11] Hertz, GDNA *Tageblatt* (1890), 149.

[12] Hirosige, *HSPS, 1* (1969), 151–209.

[13] Quincke, GDNA *Tageblatt* (1890), 149.

[14] Wiechert, Königsberg *Schriften, 35* (1894), 4–11. Wien, *Archives Néerlandaises* (2), *5* (1900), 96–107. Abraham, *Elektrizität, 2* (1905), 147ff.

described their goal as the "electromagnetic world picture." To them, only the electromagnetic aether existed. It was all that was necessary to explain the phenomena of the world.[15]

THE WAVE THEORY OF LIGHT

Throughout the second half of the nineteenth century, light was thought to be a wave propagating in an all-pervading medium. Its properties – diffraction, interference, and polarization – convinced its students that visible monochromatic light is a periodic transverse oscillation with a wavelength between about 3×10^{-5} and 7×10^{-5} cm. The origin and development of optical spectroscopy were based on this interpretation; the assignment of a numerical wavelength to each pure color of light brought great advantages in the analysis of terrestrial and astronomical matter. During the nineteenth century, radiations on both sides of the visible spectrum were discovered: the *infrared* and the *ultraviolet* or *chemical* rays, so-called because of their ability to provoke chemical reactions. Like visible light, infrared and ultraviolet light were understood to be periodic transverse waves.

Yet lacking was a physical understanding of the medium of which the undulations constitute light. This omnipresent medium – the aether – had to have seemingly contradictory properties. It had to be extremely rigid to sustain the high-frequency vibrations of light, and yet be sufficiently yielding to allow matter, such as the planets, to pass through it freely. Physicists had attempted to formulate a consistent representation of an elastic solid with such properties. Even if they had succeeded, they would have faced grave problems. The aberration of starlight indicated that the earth moves relative to the aether during its yearly revolution about the sun, but interferometric experiments failed to corroborate this effect. Moreover, if the aether were strictly analogous to an elastic solid, then a longitudinal wave traveling at a greater velocity than the transverse should have been observed. It had not been.

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[15] McCormmach, *Isis, 61* (1970), 459–97. Hertz himself rejected the electromagnetic force ontology. His *Mechanik* (1894) attributes the forces to insensible particles. McCormmach, *DSB, 6,* 340–50. For representative statements about the electromagnetic view during our general period of concern, see the proposition by Marx, *Grenzen in der Natur* (1908), and the antithesis by Kunz, *Theoretische Physik* (1907).

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Maxwell's theoretical formulation of electricity and magnetism in the 1860s offered partial answers to some of the puzzles about the luminiferous medium.[16] He proposed that light is a transverse wave traveling in a continuous medium whose stresses and strains constitute electric and magnetic forces. Like jiggles moving along a rope, oscillations perpendicular to the direction of motion of the wave should occur along the force vectors established by electrified bodies. Maxwell showed that the velocity of these waves would be close to that found for electrical signals in a wire. Even before it received experimental corroboration, the theoretical interpretation that light is a periodic electromagnetic wave provided support for the wave theory of light.

George Gabriel Stokes described in 1884 the "views respecting the nature of light which are at present held, I might say almost universally, in the scientific world."[17] He meant the wave theory of light. He regarded the idea that light is a stream of particles shot from the luminous source as "altogether exploded." "No one who has studied the subject can doubt," he said, that "light really consists of a change of state propagated from point to point in a medium."[18] The colors of thin films and diffraction phenomena show, he said, that periodicity is "naturally, almost inevitably, involved in the fundamental conception."[19]

In Germany, Hermann von Helmholtz began his lectures on the electromagnetic theory with an affirmation of the wave theory. "Hardly a doubt remained about the superiority of the wave theory compared to the emission theory" after polarization was explained by the hypothesis of transverse waves, he claimed; the emission theory is "hardly mentioned anymore."[20] Gustav Kirchhoff based his theory of diffraction in 1882, as Stokes had done before, on the assumption that "light is a transverse undulation in the aether."[21] The leading French mathematical physicist of the time, Henri Poincaré, wrote in 1888 that "of all theories in physics, the least imperfect is that of light based on the work of Fresnel and his successors."[22]

In 1888 Heinrich Hertz completed proofs that "electric waves"

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[16] Maxwell, *PM, 21* (1861), 161–75, 338–48; *23* (1862), 12–24, 85–95.
[17] Stokes, *Nature of light* (1884), viii.
[18] *Ibid.*, 25.
[19] *Ibid.*, 32.
[20] von Helmholtz, *Vorlesungen* (1897), 3.
[21] Kirchhoff, Berlin *Mb* (1882), 641.
[22] Poincaré, *Théorie mathématique de la lumière, 1* (1889), 1.