INTRODUCTION

The denouement of this book is its ninth chapter. There the intricate story of the discovery of anti-matter is set out. Each chapter preceding this attempts to secure some philosophical point, without which features of the positron discovery would be difficult to grasp.

In chapter I, 'Light', the conceptual basis of Newton's Theory of Fits is examined: did the 'crucial' experiments of Young, Fresnel, Fizeau and Foucault demolish Sir Isaac's modified corpuscular theory? Here two steps are taken towards the idea of the positron: first, the historical foundation and conceptual superstructure of the wave-particle duality are set out; secondly, the logical structure of the *experimentum crucis* is exposed. Without these, the theoretical basis and the experimental support for the positron hypothesis could hardly be appreciated. [See appendix I.]

Chapter II re-explores the dichotomy between 'Explaining and Predicting'; it is suggested that Hempel's thesis concerning the logical symmetry between these two concepts is inadequate to any description of microtheory. This conclusion constitutes a further step toward understanding the positron. The 'hole theory' of the positive electron is an explanation of things like pair creation and annihilation; none the less, as a matter of principle, this theory cannot predict when any given pair will be created. The relationship between Dirac's algebra and the Oppenheimer–Blackett expositions of the 'hole theory' must be traced with care to determine where Hempel's thesis is valuable yet also misleading.

Chapter III concerns 'Picturing'. Here we explore why classical dynamical and geometrical models of fundamental particles are untenable in principle. This discussion attempts to place the 'hole theory' into perspective, and suggests why the physical properties of the positron can never be formed into a picture, or into a nineteenth-century type of model. [See appendix II.]

Chapter IV forces a logical confrontation: 'The Correspondence Principle and the Uncertainty Principle'. There is an acute conceptual tension within quantum theory between these principles,

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and the consequences of this affect our understanding of the positron itself.

Chapter V, on 'Interpreting', purports to defend the 'Copenhagen' interpretation of quantum theory. This issue has been most exciting in recent philosophy of science. The view expounded here has not gone unchallenged: it puts forward reasons why the theses of Vigier, Bohm and Feyerabend should not perhaps be weighted as heavily as their authors wish. In any case, some sympathetic understanding of what motivated the Copenhagen interpretation is an essential part of the conceptual background to the discovery of the positive electron.

Chapter VI elaborates points within the preceding chapter. Under the title 'Some Cautions' we raise further difficulties about the Vigier–Bohm–Feyerabend approach, and urge restraint lest historical misunderstandings arise and engender conceptual ones. The one with which we are most concerned, of course, involves the positron itself.

The next chapter (VII) discusses 'Uncertainty' again. We examine some standard 'counter-instances' to the Uncertainty Relations: each of these collapses on analysis; the Uncertainty Relations are delineated as *the* conceptual foundation stone of quantum theory. Dirac's 1928 paper on the relativistically invariant, spinning electron cannot even be comprehended if the Uncertainty Relations are construed as anything less than a *theoretical* boundary condition of quantum physics. Attempts to treat the relation $PM-MP = (h/2\pi i)\psi$ *merely* as an observational limitation are shown to fail.

Chapter VIII is called 'Equivalence?'. The 'proofs' of Eckart and Schrödinger, to the effect that the Wave Mechanics and Matrix Mechanics of 1926 are equivalent, are, it is suggested, faulty in their conclusions. This chapter has stimulated some comment among theoretical physicists, and its thesis appears to be substantiable. This is in itself quite important; the 1928 paper of Dirac constitutes not simply algorithmic ingenuity, but a redesign of the very conceptual framework of then-extant quantum theory. The Dirac formalism achieves what the Schrödinger and Eckart 'proofs' could not achieve. Wave Mechanical and Matrix Mechanical solutions are both easily generable within the Dirac notation; hence this constitutes a stronger claim for the theoretical equiva-

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lence of Wave Mechanics and Matrix Mechanics than when they are represented in the original Schrödinger and Heisenberg notations. Since the positron concept derives directly from the innovations of the 1928 paper, our rejection of the proven equivalence of Wave Mechanics and Matrix Mechanics before that date constitutes an essential last step toward the discovery of the positron idea. [See appendix III.|

Chapter IX is called 'The Positron'. Here some of the intertwining strands of theory, observation, and experiment in microphysics are disentangled, with the result that we can distinguish three different discoveries within this single complex. I arbitrarily designate these 'the Anderson particle', 'the Dirac particle', and 'the Blackett particle'. The first was a truly remarkable observational discovery based on strict reasoning, but largely innocent of any complex theoretical considerations. The second constituted a dramatic theoretical advance—but one carried on, at first, in the abstract realm of the *gedankenexperiment*. Although wholly independent of each other, these first two discoveries both rebounded from a reluctance to entertain any particle except the negatron and the proton. One function of this chapter is to explore such reluctance; its roots go back into the history of electrical theory, and especially into late nineteenth-century electrodynamics. The third discovery, Blackett's, is characterized as a '*meta*-physical' discovery. In addition to constituting a primary advance in itself, Blackett's work is important for recognizing that the prior discoveries of Anderson and Dirac were the *same* discovery. From quite different directions Anderson and Dirac had *backed* into similar conclusions about the same material entity. But that this was so was not known until Blackett published his paper of 1933. [See appendix IV.]

The author's own concern with the positron concept began in 1946. As more and more has been learned of the total story, deeper analysis has sliced into each new speculation and attitude. Special conjectures of my own have been tested and modified, and usually abandoned, in conversations and correspondence with theoretical and experimental physicists, with historians of science, and with logicians. To them all I am grateful.

The positron is the first anti-particle. It was the first genuine alternative to the dominance of particle theory by the negative electron and the proton; it is at once a reluctant cause and the dramatic result of the twentieth-century conjecture that matter can be created out of energy. Many related problems of interest to historians and logicians of science literally spill from this cornucopia of physical concepts.

CHAPTER I

LIGHT

A

During the last half-century startling discoveries have been made by physicists: these have affected our understanding of heat, light, and electricity, in ways yet fully to be realized. None the less, the conceptual structure of the findings of Planck, Einstein, Compton and Dirac is by now beginning to emerge. Let us consider this structure against the three centuries of physics which preceded it, with particular reference to Newton's optical theory and the famous 'crucial experiments' to which it led.

The disturbing discoveries of the present century have concerned the notion of radiation as a continuous transfer of energy. This is just the notion and the controversy which had earlier centred on the nature of light. Was the movement of light from sun to earth an unbroken propagation of energy, analogous to rolling surf-waves? Or did it consist in a discontinuous emission of discrete packets of energy, like the peppering of a target with bullets?[1] The work of Planck, Einstein and Compton, all of it theoretically persuasive and experimentally ingenious, supported this latter conclusion.

The orthodox nineteenth-century position concerning radiant energy was elegantly and forcefully expressed in the electromagnetic wave theory of James Clerk Maxwell and H. A. Lorentz. But this position was assailed by difficulties even before Planck. Certain calculations[2] required infinite values for the total density of energy; an inconceivable state of affairs. Things worsened when Max Planck studied how hot black bodies give up and take on radiant energy. He conceived of a beautifully designed furnace, and sensitive detectors. With these he established that any such body emitted energy not continuously, but in distinct, discrete pulses: there were calm valleys between emitted pulses; intervals during which little or no radiation left the hot, black body. Planck compromised with the orthodox theory: he conceded that bodies *took in* radiation in a continuous way; but his experiments forced

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him to assert that they gave it off in equal pulses. Energy absorption was continuous; energy emission discontinuous. Planck preserved the continuity of radiation, for this alone seemed compatible with the requirements of the highly confirmed wave theory; he restricted his heresy to emission of radiation from hot bodies. Hence, Planck's theory of 1901.[1]

In 1887 the photo-electric effect was discovered by Hertz. If we charge an electroscope negatively, so that the gold leaves mutually repel each other, and then cover the upper surface with an alkaline metal (e.g. zinc), a remarkable phenomenon occurs when the apparatus is bathed in X-radiation. The electroscope loses its charge and the leaves slowly fall together. Nothing in classical electromagnetic theory accounts for this: X-rays lack charge; why should the electroscope lose charge when X-radiated? In 1905 Einstein boldly supposed X-radiation itself to be composed of the discrete pulses of energy of which Planck had spoken:[2] the action of these pulses on the matter constituting the electroscope might explain the effect. Einstein developed the idea of the photo-electron as an ordinary matter-electron, photo-electrically expelled from an electroscope. Whenever an energy pulse crashes into an electron within the matter composing the electroscope, the result is interpretable as a classical two-body problem analogous to billiard balls under impact.[3] Occasionally, however, one of the matter-electrons will be knocked out of the electroscope, carrying its charge with it; as this process continues, the total negative charge of the electroscope slowly disappears.

A. H. Compton made a further discovery in 1923 which established that, whatever else it may also be, light radiation is indisputably particulate.[4] By playing X-rays on to a carbon block and then trapping the reflected radiation in a sensitive detector, Compton revealed that the scattered rays were not all of the same frequency as the original beam. Some reflected rays had lost energy in the transaction. Again, Compton explained this by supposing a classical two-body interaction between a photon and one of the electrons in the carbon. This effect, however, differs strikingly from the photo-electric effect; here the light-corpuscles are not annihilated by their contact with matter: they bounce back, with a classical interchange of energy as between billiard balls.

Each of these discoveries bred controversy concerning the

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'proper' interpretation. That radiation should be particulate and discontinuous was too startling 40 years ago for most physicists to countenance.

Indeed, this double-stranded line of development becomes beautifully knotted in contemporary experiment.

If, in an electron microscope, a beam of electrons emitted by a filament is interrupted by a plate with a tiny hole in it, a vague splash of light will appear on the target screen beyond. This is caused by the electrons coming through the hole and then spreading out. Now make another hole very close to the first. Do we see two patches of light? No. We see the same patch, only now much brighter, and striated with several parallel dark bands. Choose now one of the brightest parts of the patch on the screen: which of the two holes do the electrons reaching that spot pass through? Cover up one of the holes and see what happens. The bright-dark striations vanish at once, and the intensity of light at the selected point falls off sharply. But this does not mean that most of the electrons were going through the hole we covered, since precisely the same effect would have been detected had we covered the other hole. The striations and the extreme brightness, in other words, are observed only when *both* holes are open. In these circumstances we simply cannot observe through which hole any particular electron passed. So here the result of the experiment is affected by any such attempt to follow it in finer detail than it seems prepared to allow. From the instant the electrons leave the filament until they impinge on the screen we are denied the luxury of looking at them: to observe is to transform.

Yet how to describe what *is* observed? The electron particles are clearly interfering in some 'classical' wave-like manner. And the resultant illumination is obviously also particulate in some fairly fundamental way. The same startling phenomena mentioned earlier seem to intertwine in this electron-microscope example.

B

Why should these findings have been startling? Nature is what it is; why should men be alarmed to learn that light is as much like a hail of fine sand as like the jiggling of a clear jelly?

The answer is familiar. Men are surprised by nature because

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they themselves make it impossible not to be surprised. Scientists make decisions concerning what certain phenomena must be like, and are then startled to learn that nature refuses to co-operate with their ideas. Sometimes we behave inflexibly in these contexts; more than one scientist has had difficulty in conceiving that nature could be other than he originally supposed it to be. To overcome this has been the province of genius.

From earliest times it had been known that certain properties of light are best explained by supposing it to be corpuscular. For example, geometrical optics, that science which examines relationships between shadow-lengths, the positions of light-sources, and the heights of illuminated objects, was established in Greek antiquity. Thales is said thus to have determined the height of the pyramids. But before such a science can be formulated, shadows must be assumed to be sharp, i.e. not to blur off indeterminately. Had this not been so, Thales could not have known *from where* to measure the pyramid's shadow. But if one considers the 'shadows' which water waves cast behind a pier, they are not at all sharp; instead of seeing a calm zone separated from the waves by a sharp boundary, the latter curl round behind the pier. Sometimes they obliterate the 'dead zone' entirely. So waves did not seem, to the ancients, a good model for light propagation. Since the shadows cast by the sun were sharp, it seemed that sunlight travelled along perfectly straight lines. Euclid, indeed, makes this the basis of his optics,[1] and of all his studies of perspective.[2] This is consistent with the idea that light resembles more a spray of fine particles than it does undulations within a thin, clear jelly. Even so, Euclid himself opposed the 'emission theory' of Pythagoras. Sand blown obliquely against a book leaves a sharply demarcated streak on the far side. Empedocles argued along these lines for a particulate theory.[3] This Principle of the Rectilinear Propagation of Light is immediately established when one considers mirror reflexions which are easily explained on the rectilinear principle and the particulate theory of light. Claudius Ptolemy[4] traces the rectilinear motion of a reflected ray by faithfully comparing it with an object thrown against a wall; and he continually speaks of a 'slinging action'. All this itself became the subject-matter of a distinct science—catoptrics—in connexion with which the great names of Euclid, Hero, Ptolemy and Alhazen stand forth.

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The particulate theory was virtually the only one concerning the nature of light until the early seventeenth century.[1] Then Grimaldi studied the shadow cast by a hair.[2] This shadow was fuzzy at its edges: indeed, as the illumination intensified the fuzziness broke up into a series of fringes or stripes running parallel to the shadow's edge. Grimaldi made the important observation that these fringes appeared not only outside the shadow's edge, but actually fell within the shadow itself. This is crucial: we shall refer to it again.

Even before Grimaldi's observation, wave motion had been studied. It was suspected that periodicity in a phenomenon, any kind of a regularly recurrent pulse, or waxing-and-waning, indicated that the event was wave-like in nature. Thus the beats emitted in the lower registers of a cathedral organ distinguished sound as consisting in a wave-like propagation of energy through air.[3] The high spots and dead calms which evenly intersperse where, on the surface of a pond, two wave fronts intersect and overlap, were construed as the same kind of phenomenon. Even things like magnetic effluvia were suspected of having this basic property. Thus Grimaldi's observation carried the suggestion that perhaps light too had a wave nature.[4] Further work by Descartes, Huygens, Newton, Euler and Hartley, brought extensive observational and theoretical support to this thesis, to which we must later return.

For the moment, it is relevant to consider the researches of Young and Fresnel which, in the early 1800's, established light as a periodic disturbance of some sort. They showed light to interfere, constructively and destructively, just as do water waves and sound waves. Young with his renowned two-slit experiment,[5] and Fresnel, with his equally famous bi-prism experiment,[6] were able to bring two distinct, yet physically identical, wave fronts of light into overlapping contact. These were made to run across each other at a small angle, just as two wave fronts of water, or air, can be made to cross and interfere. The remarkable result was that both Young and Fresnel were able to reveal on their target-screens bands of bright light alternating with dark patches.[7] From this, given that detecting such periodicity indicates the presence of wave phenomena, the Young–Fresnel experiments proved that light must consist in an undulatory propagation of energy. Nor has anything since discovered disproved their findings. But, for historical reasons to be examined, the results of their work became known not only as that which established the undulatory character of light: it was taken also to *disprove* the theory that light was in any way particulate.

Later experiments, by Fizeau (1849) and Foucault (1850), carried this logical progression further. The particle theory of Newton, La Place and Biot[1] requires that the velocity of light should increase as the radiation passes into a denser medium. Fizeau and Foucault established that this did not happen: by an ingenious experimental arrangement Foucault was able to disclose that the velocity of light in water is less than its velocity in air. This did seem crucial against the corpuscular theory. No consistent theory could allow the velocity of light in water to be at once greater than and less than its velocity in air.

A logical monument was erected by the wave theorists to commemorate this 'defeat' of the corpuscular theory. One must mention here the names of Poisson, Green, MacCullagh, Neumann, Kelvin, Rayleigh, Kirchhoff, and last, the great James Clerk Maxwell who developed the theory to a high order of precision and elegance, and applied it in totally unsuspected areas. In all this wave-theoretic work the very concepts of *particle* and *wave* came to be fashioned in logical opposition to each other. Particle dynamics on the one hand, and electromagnetic wave theory on the other, became fashioned as mutually exclusive and fundamentally incompatible concept-systems which, between them, could embrace every type of energy transfer. Even now we cannot easily conceive of a third way of propagating energy. Still, the two theories could never be applied simultaneously to the same phenomenon. A particle is a dynamical entity with sharp co-ordinates, it is in one place at one time; no two particles can share the same place at once; when particles collide there is a familiar impact and rebound. A wave disturbance, however, is fundamentally lacking in sharp co-ordinates; in principle it spreads boundlessly throughout the volume of the undulatory medium.[2] Contract a wave to a point and you destroy it; indeed, 'Wave motion at a geometrical point' gestures towards an inconceivable state of affairs.

Moreover, one can sensibly speak of two waves being in the same place at once; this is clear from observing two surf-waves crossing