The tiger and the shark

Empirical roots of wave–particle dualism

It is like a struggle between a tiger and a shark,
each is supreme in his own element,
but helpless in that of the other.
J. J. Thomson, 1925

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Bruce R. Wheaton

with a foreword by Thomas S. Kuhn

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For Ariana and Geoffrey;
may they transcend the
indeterminism of their elders

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FOREWORD

The first three decades of the twentieth century embraced two great changes in physical theory: relativity, both general and special, and quantum theory, both the old and the new. Among the innovations that constituted these theories, none was more difficult to accept and assimilate than Einstein's suggestion that light displays particulate properties, especially at high frequencies. Together with the related recognition of the wavelike properties of material particles, Einstein's light-particle theory has proved a fundamental constituent of modern physics, perhaps the single feature that most sharply distinguishes it from the generally Newtonian physics of the preceding three hundred years. But for nearly twenty years after Einstein's proposal in 1905, the concept of light-particles was almost everywhere rejected. Even R. A. Millikan, who in 1914–16 provided the first unequivocal evidence for Einstein's surprising law of photoelectric emission, continued, equally unequivocally, to disdain the light-particle hypothesis from which that law had been derived. Only after 1923, when Compton and Debye independently used the light-particle hypothesis to explain the shift in frequency of scattered x-rays, did more than a very few isolated physicists begin to take seriously the idea that electromagnetic radiation often behaves like particles.

That, in outline, is the way that historians of physics have recently been telling the story of the light-particle hypothesis, and with respect to Einstein it remains very nearly the way the story should be told. But, as Bruce R. Wheaton amply demonstrates in the pages that follow, Einstein's was only one approach to conceiving radiation as particulate. A second, far less well known, was associated with observations on x-rays and γ-rays, both discovered during the decade before Einstein's hypothesis was enunciated and neither unequivocally identified with light for another decade. By

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1900, five years after their discovery, x-rays were almost everywhere assumed to be impulses, formed when fast-moving electrons are decelerated at the target electrode of an x-ray tube and thereafter propagated radially from the target through the electromagnetic ether. This in itself, as Dr. Wheaton shows, had a significant and heretofore unappreciated effect on the early accommodation of classical ideas of radiant energy with the new quantum theory. That x-ray energy is transported by impulses required physicists to take explicitly into account the number of pulses that pass as well as their individual energies. This set the stage for a reinterpretation of radiant intensity, one that increasingly diverged from the classical dependence of electromagnetic effect on amplitude toward one in which the temporal impulse width, or later the frequency, was the determining factor.

A similar impulse explanation was widely applied by 1905 to γ-rays as well, with acceleration of an electron ejected from an atom replacing deceleration at the target of an x-ray tube. Supported by existing theories and suggested by a variety of experiences, these explanations were nevertheless difficult to reconcile with two recognized sets of observations on the ionization of gases by the new rays. Those observations were in turn the source of a continuing series of suggestions, often independent both of each other and of Einstein, that x-rays and γ-rays be viewed as particulate.

The first set of observations, readily made but not of great force by themselves, gave rise to what Dr. Wheaton calls the *paradox of quantity.* Passing through a container filled with gas, an advancing impulse should affect all gas atoms equally, but in practice it ionizes only a minuscule portion of them. How can the pulse ionize any atoms if it does not ionize all or most of them? A second set of observations, far harder to establish but also far more difficult to explain away, constitute Dr. Wheaton's *paradox of quality.* An electron torn from an atom in the process of ionization by x-rays carries with it energy of the same order of magnitude as that of the electron decelerated in forming the original impulse. It is as though, at the moment of ionization, all the energy in an isotropically expanding x-ray pulse were suddenly concentrated at the point on the pulse's spherical surface where ionization was to take place. Experimental data from which these paradoxes might have been identified were available in 1900, and more accumulated steadily thereafter. By 1908, at least two well-known experimental physicists, William Henry Bragg and Johannes Stark, had based corpuscular theories of radiation upon them. But such evidence of corpuscular properties impressed few physicists until two additional conditions were fulfilled. Less paradoxical explanations first had to be set aside, for example a variety of hypotheses that derived the energy of an ejected electron not from radiation but from the interior of the atom, radiation serving only to "trigger" emission. In addition, evidence for the paradoxes had to be refined, primarily, Dr. Wheaton shows, by the detailed study of x-ray absorption spectra and the development of techniques for β-ray spectroscopy.

With these new data in hand, it became possible to strike precise balances between the energy lost at the target by the cathrode-ray electron in an x-ray tube, the orbital energies of the interior electrons of the target atom, and the energy $h\nu$ (and thus the frequency ν) of the resulting x-ray. The last of those energies could, in turn, be shown to be equal to the sum of the kinetic energy of an electron ejected during ionization and its orbital energy prior to ejection. In the laboratories where these techniques were developed and these energy balances observed, it was impossible not to notice that, with respect to spatial localization and energetic relations, radiation behaved precisely like particles.

Those conditions were not, however, fulfilled before 1920, and then in only a very few places. One of these few was the private laboratory set up in his Paris home by the French nobleman, Maurice de Broglie. By 1921 de Broglie's laboratory had mapped the x-ray energy levels of many atoms, and during that year an improved β-ray spectrometer was used to study the velocities of the photoelectrons ejected by x-rays of known frequency. Reporting the results to the Third Solvay Congress in April of that year, de Broglie insisted that the radiation "must be corpuscular, or, if it is undulatory, its energy must be concentrated in points on the surface of the wave" (p. 270). The following year, with additional results in hand, de Broglie wrote that the phenomena "present facts in such a way that their qualities are sometimes described in terms of the wave theory, sometimes in terms of the [particulate] emission theory" (p. 277).

Remarks of that sort, both from de Broglie and others, prepared the way for a reevaluation of Einstein's work even before the particulate interpretation of the Compton effect in 1923. Furthermore, the first major contribution to that reevaluation was made starting in 1922 by Maurice's younger brother, Louis de Broglie. Louis had been trained by France's leading theoretical physicist, Paul Langevin, a man who knew and greatly admired Einstein; he had also worked closely with Maurice on the interpretation of laboratory results. Louis de Broglie was strategically placed to bring together the long-separate theoretical and experimental approaches to the concept of light-particles. In the process he took major steps toward the emergence in 1926 of Schrödinger's wave mechanics.

From Wheaton's perspective, the independence of Schrödinger's wave mechanics from the slightly earlier matrix mechanics of Heisenberg can be explained by the different emphasis each investigator placed on the paradoxes of free radiation. To Heisenberg, a product of Bohr's school, atomic structure held the center of interest. To Schrödinger, as before for Einstein and de Broglie, the nature of light and its behavior in traversing matter were the most pressing problems. Although theoretical research on both atoms and light utilized some of the same empirical data – most notably from x-ray spectroscopy – Einstein and de Broglie were virtually alone before 1923 in directing it toward a resolution of the nature of radiation. The development of two independent but ultimately equivalent forms of the new quantum mechanics thus arose in part from the lack of interest in the nature of light shown by most theoretical physicists in the decade before 1923.

The preceding remarks suggest only some main themes of Dr. Wheaton's narrative. The following pages supply others together with the rich circumstantial detail, the accounts of false starts and local triumphs that make history of science a story about people. The fascination of that detail, much of it here recorded for the first time, is for me the greatest of the rewards that Wheaton's text offers readers, but it also qualitatively alters a standard picture of the development of quantum theory. By emphasizing experiments and the people who perform them, it redresses the emphasis on abstract theory characteristic of most previous historical literature on quantum theory. Simultaneously, by emphasizing x- and γ-radiation, it redresses that literature's special emphasis on optical spectra. These two changes may, in turn, permit a third. Dr. Wheaton's is the first account of quantum theory known to me in

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which Louis de Broglie appears less as a surprising intruder than as a person with just the background required to play the role for which he is known.

THOMAS S. KUHN

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PREFACE

> Leopards break into the temple and drink dry the sacrificial pitchers; this occurs again and again until it can be predicted, and it becomes part of the ceremony.
> F. Kafka, 1935

The first years of this century witnessed the final rejection of determinism in physical theory; there is no more compelling example of this than the synthesis forged in the early 1920s between theories of matter and theories of light. The insight of Louis de Broglie that led to the most complete formulation of wave–particle dualism was the last act in a series of preliminary attempts by physicists to resolve paradoxes that had arisen in theories of radiation following the discovery of x-rays. Historians have not directed sufficient attention either to radiation theory or to experimental studies of recent physics. In the case at hand, significant empirical data were recognized to challenge classical radiation theory long before the theory was successfully modified to agree with them. The gradual recognition, based on these experimental results, that internal consistency is unattainable by electromechanical interpretations of radiation forms the subject of this book.

This study grew out of concerns first raised while I was a student of physics. The inadequacy of most textbook discussions of historical and epistemological issues led me back to the original papers and then to the literature on history of science. I was fortunate to be introduced to the latter by John Heilbron, whose critical approach and demand for clarity in expression showed how insight can be won in historical analysis of scientific thought. When I undertook a study of the photoelectric effect – the liberation of electrons from metals by ultraviolet light[1] – I found that many of the textbook accounts that had confused me were demonstrably false when viewed historically.[2]

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[1] Wheaton, *Photoelectric effect* (1971). Abbreviations used in the footnotes and the bibliography are identified in the notes on sources.

[2] For example, see Eisberg, *Fundamentals* (1961), 76–81; Jammer, *Conceptual development* (1966), 35.

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After an invaluable exposure to the modern descendant of the European culture within which these issues developed, I was again fortunate to have the opportunity to work on the more general historical problem of wave–particle dualism with Thomas Kuhn as guide. When I extended my original concerns to include high-frequency radiations, I found that the experimental evidence amassed by 1911 concerning x-rays played a far more significant role in preparing physicists to accept dualistic theory than did evidence regarding ordinary light. My doctoral dissertation formed the second stage in the development of this book.[3] In it I clarify the extent to which the then standard impulse interpretation of x-rays led to an implicit tension of a kind destined to bring reformulation of classical concepts regarding the distribution of energy in all forms of radiation in the 1920s.

But the story does not end there, and in this book I bring the discussion to its historical conclusion. The results of attempts to force consistency on electromechanical interpretations of radiation rebounded to affect also the theory of matter. While reconsidering Einstein's lightquantum hypothesis in 1921, Louis de Broglie tried to find a theory of light that would combine the macroscopically incompatible representations of wave and particle. He based this work on the solid foundation provided by his elder brother's experimental corroboration of Einstein's photoelectric law for x-rays. The result in 1923 was a hypothetical synthesis of matter and light: Each was to be considered to possess both particle and wave attributes that make their presence felt to a greater or lesser extent according to experimental conditions. The successful elaboration of this remarkable hypothesis signaled the end of strictly deterministic representations of both matter and of light.

The reader may wonder why the name of Albert Einstein does not figure more heavily in this account of evolving understanding that neither a wave nor a particle characterization of radiation is alone sufficient. After all, Einstein introduced the lightquantum hypothesis in 1905 and early on recognized that a synthetic theory was needed. The reasons are straightforward. Einstein's revolutionary hypothesis had almost no followers and very little influence before 1921, and the growth of its acceptance by others marks the limit of our direct concerns. His lightquantum was not initially intended to apply either to x-rays or to γ-rays, but rather only to

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[3] Wheaton, *Nature of x- and gamma rays* (1978).

visible and ultraviolet light. Before 1911 it was not clear to most physicists that x-rays and visible light are common species of radiation. Consequently the experimental evidence that had accumulated by that time that x-rays and γ-rays *do* transfer energy in individual units did not justify Einstein's lightquantum in the eyes of most physicists. The difficulties of any corpuscular theory in explaining interference properties of radiation were too formidable. And for almost a decade following Niels Bohr's quantum theory of the atom in 1913, most mathematical physicists showed little interest in the paradoxes that complicated a consistent electromechanical interpretation of free radiation.

Thus, our story developed quite independently of the imaginative and prescient statistical treatment of light of which Einstein was the chief architect. Einstein's own developing realization of the need for duality in radiation theory has been discussed historically by Martin Klein.[4] Here we analyze other physicists' efforts to wrestle with closely related issues, discuss their rejection of and eventual accommodation to dualistic ideas in physical theory, and trace the way in which this development came to alter ideas not simply about radiation and matter but about humans' ability to construct consistent models of physical phenomena based on their experiences in the macroscopic world of human senses.

The present narrative evolved out of an extensive search in the physics literature of the period, all significant results of which appear in the notes. Documents in several manuscript collections, some in archives and others privately held, were invaluable for reconstructing contemporary insights and opinions, for supporting evidence, and for opening new areas for research. In particular, I benefited from examination of the Archive for History of Quantum Physics,[5] the Bohr archive, the Cherwell papers, the Einstein archive, Paul Langevin's papers, the Lorentz papers, holdings of the Nobel archives, the archives of the Paris Academy of Sciences, the Rutherford papers, the Schwarzschild papers, and the archives of the Solvay Institute. Full identifications and locations of these and other collections are given in the notes on sources. I am grateful to these and other repositories for the kind access granted me, and to the holders of literary rights for permission to quote documents. I was greatly assisted in my research by

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[4] Klein, *Natural philosopher, 3* (1964), 3–49.

[5] Described in Kuhn, Heilbron, Forman, and Allen, *Sources* (1967).

concurrent work on the *Inventory of sources for history of twentieth-century physics,* being led to several important and formerly untapped collections.[6] The immense quantity of data the ISHTCP has compiled and their as yet incomplete description encourage further mining of their riches.

An undertaking of this magnitude is possible only with the help of colleagues and of prior work in the field.[7] I am pleased here to acknowledge debts of both sorts. I am grateful for the comments of several anonymous reviewers of the typescript before publication. I have already mentioned the importance of Martin Klein's work on the early work of Einstein; other studies by him are mentioned in the Notes. The quantum interpretation of the Compton effect in 1922 was an event of great significance; Roger Stuewer's detailed review of the evolution of Compton's approach to it made it unnecessary to recount that episode in depth here.[8] Although Stuewer's and my interpretations differ on the importance of the electromagnetic impulse hypothesis of x-rays and about the renaissance of interest in the lightquantum, his study is a significant addition to the meager literature on the development of experimental physics in this century.[9]

I have been fortunate, professionally and personally, in my own introduction to history of science to have had as guides both Thomas Kuhn and John Heilbron. I have benefited greatly from discussions with both on many aspects of physical theory. Professor Kuhn's reassessment of the conceptual origins of quantum theory has influenced this study in many ways.[10] Only one who has had the benefit of his insightful criticism and sympathetic ear can understand how much of a debt I owe him. His conceptualization of scientific advance encourages historical analysis within which the humanistic aspects of science are no longer submerged in mythic objectivity. We are all in his debt for that insight.

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[6] This inventory identifies the location, author, recipient, and approximate date of half a million letters from or to physicists active between 1896 and 1952. It will soon be published in microfiche/book form. Contact Springer Verlag, New York for information on ordering.

[7] For background on the material basis of national style in physics, see Forman, Heilbron, and Weart, *HSPS, 5* (1975), 1–185.

[8] Stuewer, *Compton effect* (1975).

[9] For the neglect of experimental physics, see Heilbron and Wheaton, *Literature* (1981).

[10] Kuhn, *Black-body theory* (1978).

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I would be pleased if this study of radiation theory were taken as complementary to John Heilbron's analysis of concurrent developments in atomic theory.[11] Matter and light are the two perceivable manifestations of nature. Their interaction provided the evidence that showed that electromechanical representations of nature would fail. But although the classical–quantum compromise inherent in the Bohr theory of the atom acted to delay recognition of failure for the electromechanical atom until the early 1920s, the paradoxical behavior of radiation was evident to some as early as 1908. The problems that led to the rejection of deterministic physical theory presented themselves early, and most clearly, in attempts to bring consistency to the theory of radiation.

BRUCE R. WHEATON

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[11] Heilbron, *Atomic structure* (1964); contribution in *Twentieth century physics* (1977), 40–108.

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NOTES ON SOURCES

PUBLISHED SOURCES

All works cited in short form in the footnotes will be found in the bibliography under the author's name, but the footnote references are intended to be sufficient to lay hands on the work itself. In general, and following Library of Congress practice, names of journals are listed under the name of the issuing organization. Because many are cited frequently I have used the following abbreviations:

AHES	*Archive for History of Exact Sciences*
AJP	*American Journal of Physics*
AJS	*American Journal of Science*
Amsterdam	Koninklijke Akademie van Wetenschappen te Amsterdam. Wis- en Natuurkundige Afdeeling
AP	*Annalen der Physik*
ASPN Genève	*Bibliothèque universelle. Archives des sciences physique et naturelle, Genève*
AusAAS	Australasian Association for the Advancement of Science
BAAS	British Association for the Advancement of Science
Berlin *Mb, Sb*	Königliche preussische Akademie der Wissenschaften, Berlin. Physikalisch-mathematische Klasse, *Monatsberichte, Sitzungsberichte*
BJHS	*British Journal for the History of Science*
Bologna	Reale Accademia della Scienze dell'Istituto di Bologna
CR	Academie des Sciences, Paris. *Comptes rendus hebdomadaires des séances*
DSB	*Dictionary of Scientific Biography,* 14 vols., C. C. Gillispie, ed. (New York, 1970–6)

GDNA	Gesellschaft Deutscher Naturforscher und Ärzte
Göttingen	Königliche Gesellschaft der Wissenschaften zu Göttingen
Halle	Naturforschende Gesellschaft zu Halle
Heidelberg *Sb*	Heidelberger Akademie der Wissenschaften, *Sitzungsberichte* (listed by Abhandlung number)
HSPS	*Historical Studies in the Physical Sciences*
JFI	Franklin Institute, *Journal*
JHI	*Journal of the History of Ideas*
JP	*Journal de physique et le radium*
JRE	*Jahrbuch der Radioaktivität und Elektronik*
Königsberg	Physikalisch- ökonomisch Gesellschaft zu Königsberg
Lincei	Reale Accademia dei Lincei, Rome
Manchester *MP*	Manchester Literary and Philosophical Society, *Memoires and Proceedings*
München *Sb*	Königliche Bayerische Akademie der Wissenschaften zu München, *Sitzungsberichte*
NAS	National Academy of Sciences, Washington, D.C.
NNGC	Nederlandsch natuur- en geneeskundig congres
NRC	National Research Council, Washington, D.C.
PCPS	Cambridge Philosophical Society, *Proceedings*
PM	*Philosophical Magazine*
PPSL	Physical Society of London, *Proceedings*
PR	*Physical Review*
PRI	Royal Institution, *Proceedings*
PRS	RSL, *Proceedings*
PTRS	RSL, *Philosophical Transactions*
PZ	*Physikalische Zeitschrift*
RGS	*Revue général des sciences pures et appliquées*
RDS *Sci trans*	Royal Dublin Society, *Scientific Transactions*
RSL	Royal Society of London
SFP *PVRC*	Société Française de Physique, *Procès-verbaux et résumé des communications*
SHPS	*Studies in History and Philosophy of Science*
TCPS	Cambridge Philosophical Society, *Transactions*
TPRRSSA	Royal Society of South Australia, *Transactions and Proceedings and Report*
VDNA	GDNA, *Verhandlungen*
VDpG	Deutsche physikalische Gesellschaft, *Verhandlungen* (usually bound with *Berichte*)
VI	Victoria Institute
WAS	Washington Academy of Science
Wien *Sb*	Kaiserlich-Königliche Akademie der Wissenschaften,

	Wien. Mathematisch-naturwissenschaftlichen Klasse, *Sitzungsberichte*
Würzburg *Sb*	Physikalisch-medizinische Gesellschaft zu Würzburg, *Sitzungsberichte*
ZP	*Zeitschrift für Physik*
Zürich	Physikalische Gesellschaft zu Zürich

UNPUBLISHED SOURCES

A work of this kind depends on both published and unpublished records of contemporary opinion and results. We are fortunate that the subject at hand developed after the typewriter was invented and before the telephone was widely used. Carbon copies of typed letters double the chance that they will be retained, and the lack of telephone use encourages creation of a written record.

In my research I used many sources of unpublished documents, and I am indebted to several people for permission to quote from them: Victor de Pange for permission to quote Maurice de Broglie, the American Friends of the Hebrew University to quote Albert Einstein, Mme. Luce Langevin to quote Paul Langevin, Dr. Bent Nagel to quote transactions of the Nobel Prize committee, and Ruth Braunizer for permission to quote Erwin Schrödinger. I am grateful to Professor Louis de Broglie, who graciously set aside several hours for a discussion with me about this research. Of course I, not he, am answerable for the interpretation given here.

I am no less grateful to many other libraries and archives in Europe and America for making their collections of correspondence available to me. Consulting them was essential for background information, for leads to new sources, and to ensure that the general picture I painted was true to life. Many of the letters cited here are quoted in part or whole in other published works. References appear in the microfiche index *An inventory of published letters to and from physicists,* 1900–1950, listed in the bibliography under Wheaton and Heilbron (1982). Many letter collections related to modern physics are now described in detail in the *Inventory of sources for history of twentieth-century physics* (a database soon to be published in microfiche/book form by Springer Verlag) including all that are noted below, save the Nobel archives.

AHQP. Archive for history of quantum physics. Berkeley, Copenhagen, Minneapolis, New York, Philadelphia, and Rome. Microfilm references follow the form "*x, y*" where *x* is reel number, *y* is section number. For a description, see Kuhn, Heilbron, Forman, and Allen, *Sources* (1967). Sources marked with a *are available on microfilm at several of these locations

Bohr (Niels) archive.* Niels Bohr Institutet, Copenhagen, Denmark

L. de Broglie dossier. Archives of the Academie des Sciences, Paris

Cherwell (F. A. Lindemann) papers. Nuffield College Library, Oxford, England

Ehrenfest (Paul) archive.* Museum Boerhaave, Leiden, Netherlands

Einstein (Albert) papers. Institute for Advanced Study, Princeton, New Jersey

Langevin (Paul) papers. Formerly privately held in Paris, now at "Fonds des ressources historique Langevin," Ecole superieur de physique et chemie de la ville de Paris, France.

Lorentz (Hendrik) papers.* Algemeen Rijksarchief, the Hague, Netherlands

Nobel archives. Nobelstifting, K. Vetenskapsakademiens Nobelkommitteer, Stockholm, Sweden

Planck (Max) papers.* Staatsbibliothek Preussischer Kulturbesitz, Berlin

Richardson (Owen) papers.* Humanities Research Center, University of Texas at Austin

Rutherford (Ernest) papers. Cambridge University Library, Cambridge, England

Schrödinger (Erwin) papers.* Privately held in Alpbach, Austria

Schwarzschild (Karl) papers.* Niedersächsische Staats- und Universitätsbibliothek, Göttingen

Solvay (Institute) archives. Archives de l'Université Libre, Brussels, Belgium

Sommerfeld (Arnold) papers. Sondersammlung, Deutsches Museum, Munich