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How ideas became knowledge: The light-quantum hypothesis 1905–1935

"hν"
(To the tune of "Men of Harlech")

All black body radiation
All the spectrum variations
All atomic oscillations
Vary as "*hν*"

Chorus.
Here's the right relation,
Governs radiation,
Here's the new
And only true,
Electrodynamical equation;
Never mind your d/dt^2
Ve or half mv^2
(If you watch the factor "c^2")
's equal to "*hν*."

. . .

There would be a mighty clearance,
We should all be Planck's adherents,
Were it not that interference
Still defies "*hν*."[1]

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1. G. Shearer, "*hν*," *Cavendish Society Post-Prandial Proceedings*, as reprinted in G.W.C. Kaye, *X-rays* (London, 1923, 1929), xvi.

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IN THIS ARTICLE I describe the reception of Albert Einstein's Light Quantum Hypothesis (LQH), proposed in 1905 and elaborated in later papers, by the European-American physics community. How and when did it become generally agreed that light (and electromagnetic radiation in general) has a particle character along with its well-established wave character? To answer this question it is necessary to look not only at published research papers that often simply use a hypothesis without explaining why but also at reviews, monographs, and textbooks. What reasons did authors of publications on quantum theory, optics, and general physics give for treating the LQH as established knowledge or at least as a plausible assumption?

My conclusions are only tentative, since I have not had the opportunity to examine all the unpublished letters and notebooks of all the physicists active in the first quarter of the 20th century; and even if I had done so, I still could not claim to have discovered the "real reasons" for their acceptance. But it is still worthwhile to present these preliminary results. If a survey of the published literature represents only a first approximation, while a comprehensive study of documents could give a better estimate and a psychosocial analysis of the attitudes, educational and cultural backgrounds of these physicists might provide a third approximation, one must admit that many of the judgments that scientists and historians make about why a theory was accepted are based on remarks by only a very few members of the relevant community: these judgments are scarcely better than a *zeroth* approximation.

My discussion of this question follows the general approach I have used to study other cases in the history of modern physical science; I would like to be able to compare theory-change in different sciences to see if any common features or important differences can be identified.[2]

One of my conclusions is that the reception of the LQH was favorably influenced by J.J. Thomson's proposal (before 1905) of a more qualitative corpuscular theory of radiation.

2. Brush, "Prediction and theory evaluation in physics and astronomy," in Kox and Siegel, eds., *No truth except in the details* (Dordrecht, 1995), 299–318 and works cited therein; "Dynamics of theory change: The role of predictions," *PSA 1994: Proceedings of the 1994 biennial meeting of the Philosophy of Science Association*, Hull et al., eds., vol. 2, *Symposia and invited papers* (East Lansing, MI, 1995), 133–145; "Dynamics of theory change in the social sciences: Relative deprivation and collective violence," *Journal of conflict resolution, 40* (1996), 523–545; "The reception of Mendeleev's periodic law in America and Britain," *Isis, 87* (1996), 595–628; "Dynamics of theory change in chemistry," *Studies in history and philosophy of science, 30* (1999), 21–79, 263–302; "Why was relativity accepted?" *Physics in perspective, 1* (1999), 184–214; "How theories became knowledge: Morgan's chromosome theory of heredity in America and Britain," *Journal of the history of biology, 35* (2002), 471–535.

Russell McCormmach was probably the first historian to give a detailed account of Thomson's ideas about the nature of light, in a 1967 article in *The British journal for the history of science*. In the same year he published "Henri Poincaré and the quantum theory" in *Isis*. Three years later, as editor of *HSPS*, he published Martin Klein's article on the debate between Albert Einstein and Niels Bohr on the nature of light. In 1986, with Christa Jungnickel, McCormmach published a general survey of the history of modern theoretical physics as it was developed in Germany from 1870 to 1925, providing the essential context needed to understand the quantum revolution in general and the establishment of the quantum theory of radiation in particular.[3] Rereading these publications has contributed substantially to the research described in the present article.[4]

3. Russell McCormmach, "J.J. Thomson and the structure of light," *British journal for the history of science, 3* (1967), 362–387; "Henri Poincaré and the quantum theory," *Isis, 58* (1967), 37–55. Martin J. Klein, "The first phase of the Bohr-Einstein dialogue," *HSPS, 2* (1970), 1–39. Christa Jungnickel and Russell McCormmach, *Intellectual mastery of nature: Theoretical physics from Ohm to Einstein*, vol. 2, *The now mighty theoretical physics 1870–1925* (Chicago, 1986).

4. General works on this topic include: Edmund Whittaker, *A history of the theories of aether and electricity*, vol. 2, *The modern theories 1900–1926* (London, 1953); Max Jammer, *The conceptual development of quantum mechanics* (New York, 1965, 2nd edn., 1989); Armin Hermann, *The genesis of quantum theory (1899–1913)* (Cambridge, 1971); Roger H. Stuewer, *The Compton effect: Turning point in physics* (New York, 1975); Thomas S. Kuhn, *Black-body theory and the quantum discontinuity, 1894–1912* (Oxford, 1978); Jagdish Mehra and Helmut Rechenberg, *The historical development of quantum theory*, vol. 1, Part 1, *The quantum theory of Planck, Einstein, Bohr and Sommerfeld: Its foundation and the rise of its difficulties 1900–1925* (New York, 1982); Bruce R. Wheaton, *The tiger and the shark: Empirical roots of wave-particle dualism* (Cambridge, 1983); Gerald Holton, "On the hesitant rise of quantum physics in the United States," in his *Thematic origins of scientific thought, Kepler to Einstein* (Cambridge, rev. edn. 1988), 147–187; Katherine Russell Sopka, *Quantum physics in America: The years through 1935* (New York, 1988); Helge Kragh, *Quantum generations: A history of physics in the twentieth century* (Princeton, 1999); John Stachel, "Einstein's light-quantum hypothesis: Or why didn't Einstein propose a quantum gas twenty years earlier," in Don Howard and John Stachel, eds., *Einstein: The formative years, 1879–1909* (Boston, 2000), 231–251; Laurie M. Brown, "The Compton effect as one path to quantum electrodynamics," *Studies in history and philosophy of modern physics, 33B* (2002), 211–249; Alexei Kojevnikov, "Einstein's fluctuation formula and the wave-particle duality," in Yuri Balashov and Vladimir Vizgin, eds., *Einstein studies in Russia* (Boston, 2002), 181–228; Roger H. Stuewer, "The experimental challenge of light quanta," in Michel Janssen and Christopher Lehner, eds., *Cambridge companion to Einstein* (Cambridge, forthcoming). The "instant history" of Orest D. Chwolson is also useful, *Die Physik 1914–1926* (Braunschweig, 1927).

1. FORMULATION OF THE LIGHT QUANTUM HYPOTHESIS

This section introduces Einstein's hypothesis and relates it to the physics of its time. In sections 2 and 3, I elaborate on two specific questions: why was there such strong resistance in the physics community to the proposed particulate nature of light, and in particular why did Max Planck, widely known as the founder of quantum theory, reject its application in this case? Sections 4, 5, and 6 present the theoretical proposals of Einstein and Compton and their experimental testing by Millikan, Compton and others; these sections are relatively brief because several other historians have already written excellent accounts. Section 7 takes up at greater length the reception of the LQH and other particulate theories *before* the publication of Compton's definite work in 1923, in an attempt to resolve an old question that is central to this paper: what consensus, if any, had the physics community reached? This is still controversial among historians, and more evidence is needed. Section 8 reviews the acceptance of the LQH *after* 1923, and calls attention to a new question: if physicists agreed that the Compton effect, along with the refutation of the Bohr-Kramers-Slater alternative hypothesis, provided the strongest evidence, why did physics textbooks continue to give equal or greater weight to the photoelectric effect?

Albert Einstein wrote in 1905 that "The wave theory of light . . . has been excellently justified for the representation of purely optical phenomena and it is unlikely ever to be replaced by another theory." But "optical observations refer to time averages and not to instantaneous values" and may not apply to "phenomena of the creation and conversion of light." Instead, "black-body radiation, photoluminescence, the production of cathode rays by ultraviolet light and other phenomena . . . can be better understood on the assumption that the energy of light is distributed discontinuously in space." After reviewing the theory of black-body radiation and comparing it with the theory of systems of molecules in gases and in dilute solutions, using Boltzmann's statistical theory of entropy, Einstein discussed photoluminescence. "Consider monochromatic light which is changed . . . to light of a different frequency." If we assume that "both the original and the changed light consist of energy quanta" whose magnitude is proportional to their frequency, it is clear that "the energy of a final light quantum can, according to the energy conservation law, not be larger than that of an initial light quantum" hence its frequency must be lower; "this is the well-known Stokes' rule." Then, in the next-to-last section he applied his quantum hypothesis to photo-electric phenomena and derived an equation stating that the maximum kinetic energy of the electron ejected from a solid by light must be equal to the energy of one quantum of light minus a constant characteristic of the solid (which may be related to the work needed to free a single electron from a molecule. From this equation he predicted that the maximum kinetic energy of a photoelectron should vary linearly with the frequency of the light striking the metal, since the photoelectron is ejected as a result of being hit by just one quantum of light.[5]

Einstein later showed that Planck's law could be derived from the assumption that the radiation is in thermal equilibrium with molecules whose internal energy is distributed over a discrete set of states, as postulated in Bohr's 1913 theory of the hydrogen atom. In this important paper, first published in 1916 and reprinted in a more widely circulated journal in 1917, he introduced the concept of stimulated emission of radiation, which provided (many years later) the theoretical basis for the "laser"; he also showed (as had been stated earlier by Johannes Stark) that the light quanta carry not only energy $h\nu$ but also momentum $h\nu/c$ in a definite direction.[6]

According to Jungnickel and McCormmach, "The reasoning behind Einstein's proposal of light quanta in 1905 did not convince his colleagues at the time: Planck, Laue, Wien, Sommerfeld, and other early supporters of Einstein's relativity theory all rejected his hypothesis of light quanta. Their principal argument was that interference phenomena—and also diffraction, refraction, and other phenomena of physical optics—demanded a wave interpretation of light." Lorentz "was also unpersuaded." "German physicists did not see the need for so 'radical' a step, as Planck put it. . . . Only one other leading German physicist advocated light quanta at this time, the experimentalist Johannes Stark." But Henri Poincaré in France and Paul Ehrenfest in Russia argued that the existence of quanta could be deduced directly from Planck's law.[7]

Even Robert A. Millikan, whose own experiments confirmed Einstein's prediction of the maximum energy of photoelectrons, refused to accept the hypothesis from which the prediction had been derived. He admitted that J.J. Thomson's theory met some of the objections to Einstein's theory (but still did not explain interference).

5. Albert Einstein, "Über einen der Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt," *Annalen der Physik* [series 4], *17* (1905), 132–48. John Stachel et al, eds., *The collected papers of Albert Einstein*, vol. 2 (Princeton, 1989) 134–66, including an extensive "Editorial note." English trans. in Dirk ter Haar, *The old quantum theory* (Oxford, 1967), 91–107.
6. Albert Einstein, "Zur Quantentheorie der Strahlung," *Mitteilungen der Physikalischen Gesellschaft Zürich, 16* (1916), 47–62, reprinted in *Physikalische Zeitschrift, 18* (1917), 121–128. "All radiation emitted by atoms, induced by atoms . . . is indeed directed. . . . There is no radiation in spherical waves." "With this, the existence of light quanta is practically assured"—Einstein, letter to M. Besso, 6 Sep 1916 (both quotations are in his *Collected papers*, *6*, p. xxiv).

On Stark's contribution see Stuewer (ref. 4), 30–37.
7. Jungnickel and McCormmach (ref. 3), 305. McCormmach, "Henri Poincaré" (ref. 3). Martin J. Klein, *Paul Ehrenfest*, vol. 1, *The making of a theoretical physicist* (New York, 1970), 245–257. Luis Navarro and Enric Pérez, "Paul Ehrenfest on the necessity of quanta (1911): Discontinuity, quantization, corpuscularity, and adiabatic invariance," *Archive for history of exact sciences, 58* (2004), 97–141.

While Thomson's theory was forgotten by most physicists after the 1920s, it may have helped to keep the LQH alive by reminding scientists that the "discoverer of the electron" took seriously the idea that light could be particulate.[8]

Another reason for giving some consideration to particle theories was the well-known fact that x-rays seemed to behave like particles in some respects; yet they also behaved like light, as was shown by the discovery of x-ray diffraction. By 1920 it was generally agreed that infrared, light, ultraviolet, x-rays, and gamma rays are all part of a single "electromagnetic spectrum": they are all the same kind of entity, differing from each other only in the value of quantitative parameter, wavelength, or frequency. Hence if x-rays can behave like particles as well as like waves, so can light.[9]

But some prominent physicists were reluctant to admit that light is corpuscular, because that seemed incompatible with phenomena like interference that demanded a wave explanation. In particular, Niels Bohr rejected the light quantum hypothesis as a description of the nature of light moving through space, although his atomic theory assumed that electrons absorb or emit radiation in quantized amounts in going from one state to another.[10]

2. THE WAVE THEORY OF LIGHT

As is well known, the Newtonian particle theory of light was replaced in the early 19th century by a wave theory, as a result of the work of Thomas Young in Britain and Augustin Fresnel in France. To understand the reception of the Light Quantum Hypothesis, we need to consider which properties of light were believed,

8. Robert A. Millikan, "A direct photoelectric determination of Planck's '*h*'," *Physical review* [series 2], *7* (1916), 355–388; *The electron: Its isolation and measurement and the determination of some of its properties* (Chicago, 1917), 221–238. Wheaton (ref. 4), p. xvi. Laurie M. Brown, "The Compton effect as one path to quantum electrodynamics," *Studies in history and philosophy of modern physics, 33B* (2002), 211–249, on 213. Pais, "Einstein and the quantum theory," *Reviews of modern physics, 51* (1979), 863–894. J.J. Thomson, "On a theory of the structure of the electric field and its application to Röntgen radiation and to light," *Philosophical magazine, 19* (1910). McCormmach, "J.J. Thomson" (ref. 3). Millikan (ref. 2), 238, calls it the "Thomson-Einstein semicorpuscular theory." Thomson's theory was still associated with the LQH as late as 1933; see Oliver J. Lodge, *A century's progress in physics* (London, 1927), 13; Edwin B. Wilson, "Some recent speculations on the nature of light," *Science, 65* (1927), 265–271; Herbert Stanley Allen, *The quantum and its interpretation* (London, 1928), 4; G. Juvet, *La structure des nouvelles théories physiques* (Paris, 1933), 97–98.
9. W. Friedrich, P. Knipping and M. Laue, "Interferenz-Erscheinungen bei Röntgenstrahlung," *Sitzungsberichte, Königlich bayerische Akademie der Wissenschaften zu München, 42* (1912), 303–322. Wheaton (ref. 4), part 4.
10. Klein (ref. 3), 21–28. *Niels Bohr collected works*, vol. 2, *Work on atomic physics (1912–1917)*, ed. Ulrich Hoyer (Amsterdam, 1981).

a century later, to prove its wave nature. One of them, as indicated in the last few words of the song quoted at the beginning of this article, was *interference*: the fact that the intensity of a pattern formed by combining two beams of light could in some places be *less* than the intensity of either one observed separately, as well as *more* in other places. This can easily be explained by the wave theory, if the waves are vibratory motions of a medium and those motions can either reinforce or cancel each other. The particle theory seemed to offer no explanation at all for this phenomenon.

Another property is the *speed of light in substances of different density.* According to the Newtonian particle theory, light should travel faster in a denser medium (water or glass) than in a rarer one (air or vacuum), while according to the wave theory as developed by Christiaan Huygens, the opposite should be the case. This experiment could not be done until the middle of the 19th century, because of the difficulty of measuring the speed of light in a terrestrial laboratory. When it was done in 1850 by A.H.L. Fizeau and J.B.L. Foucault, the result was unequivocally in favor of the wave theory. But that was too late to have any impact on the debate, since by that time almost all physicists had already accepted the wave theory for other reasons. Nevertheless it was used in early-20th century textbooks as a justification for the wave theory, since it seemed clearly to refute the particle theory and was perhaps considered easier to explain to students than the evidence from interference.

It was well known that Maxwell's electromagnetic theory of light predicted the existence of waves longer and shorter than visible light, although Maxwell himself was rather vague about this. Heinrich Hertz's experimental confirmation of this prediction was regarded as support for the existence of an ether but not for any comprehensible physical mechanism; Hertz could not understand Maxwell's theory and simply declared that Maxwell's theory *is* Maxwell's equations. Another successful prediction was radiation pressure, confirmed by Lebedev in Russia and by Nichols and Hull in the United States around 1900. (This would probably have been regarded as evidence for a particle theory if Maxwell's theory had not predicted it.)

At the beginning of the 20th century the wave theory was still generally accepted by physicists; its ability to explain interference was often mentioned in books on optics and sometimes in general physics texts.[11] The Fizeau-Foucault result was cited more frequently, especially in general physics textbooks, perhaps because it was easier to explain.[12] The only disagreement was on the physical

11. Paul Drude, *Lehrbuch der Optik* (Leipzig, 1900); Robert A. Millikan and J. Mills, *A short university course in electricity, sound, and light* (Boston, 1908); Henry Crew, *General physics: An elementary text-book for colleges* (3rd edn., New York, 1916).
12. Drude (ref. 11); Thomas Preston, *The theory of light,* ed. C.J. Joly (3rd edn. London, 1901), Edwin Edser, *Light for students* (London, 1902, rept. 1919); C. Riborg Mann, *Manual of advanced optics* (Chicago, 1902); Albert A. Michelson, *Light waves and their uses* (Chicago, 1903); W. Watson, *A text-book of physics* (4th edn., New York, 1905); G.A. Wentworth and G.A. Hill, *A text-book of physics* (rev. edn., Boston, 1905); Robert A. Houstoun, *Intermediate light* (London, 1925), 198.

nature of the waves and of the medium in which they travel. The Fresnel-Young model of vibrations in a space-filling ether was somewhat implausible because the ether would have to be an elastic solid in order to support the transverse waves needed to account for polarization. Maxwell's electromagnetic wave theory, while somewhat more abstract, seemed to avoid this difficulty and thus was usually employed in more advanced works.[13] A few authors asserted that there was no satisfactory theory of light since neither the elastic solids nor electromagnetic fields really *explain* light, they just give *equations* from which observable results can be computed.[14] Surprisingly, several texts presented the Newtonian particle theory as an alternative because it provided a simpler explanation of rectilinear propagation and shadows, even though it had to be (reluctantly) abandoned because the more-complex wave theory was required in order to explain more-complex optical phenomena.[15]

One of the first indications that the wave theory might need to be amended came from studies of the ionization of gases by x-rays. Only a very small number of the gas molecules emit electrons. If the x-rays are electromagnetic waves, continuously filling the space occupied by the gas, one would expect that all (or none) of the molecules would be ionized. This kind of phenomenon led J.J. Thomson, before Einstein proposed the LQH, to suggest a particulate theory. His particles were not tiny spheres or parallelepipeds as in Newton's theory but tubes of electric force as conceived by Michael Faraday. He did not reject Maxwell's electromagnetic wave theory but suggested that the wave front, rather than being continuous, might be "speckled" by regions of high intensity.

3. WHOSE QUANTUM THEORY?

The familiar equation $E = h\nu$, expressing the Light Quantum Hypothesis, was (with different notation) first given by Max Planck in 1900, and the proportionality constant h was later called "Planck's constant." For several decades it was generally assumed, therefore, that Planck himself was the first to propose the LQH. The topic of this paper would then be "the reception of Planck's quantum hypothesis." But in 1978, Thomas S. Kuhn argued that the E in Planck's equation did not originally refer to the energy of a light particle moving in free space, but to a hypothetical "energy element" possessed, gained, or lost by an atomic "resonator."

13. See books by Drude (ref. 11), Mann (ref. 12), E.L. Nichols and W.S. Franklin, *The elements of physics*, vol. 3, *Light and sound* (New York, 1903); W.S. Franklin and Barry Macnutt, *Light and sound* (New York, 1909); Richard C. Maclaurin, *Light* (New York, 1909).
14. Michelson (ref. 12); Arthur Schuster, *An introduction to the theory of optics* (London, 1904).
15. Preston (ref. 12); Mann (ref. 12).

The assumption that the resonator has an integer number of energy elements was only a mathematical device used to facilitate combinatorial calculations (how many ways can you distribute the total energy among a certain number of resonators?), not a physical postulate.[16]

Since Einstein, in 1905, was the first to explicitly advocate the LQH, our topic is the reception of *Einstein*'s light quantum hypothesis.[17] Planck's distinction is to be the first to explicitly reject it.

Kuhn and other historians have presented the evidence that Planck in 1900 did not propose physical quantization of electromagnetic radiation. I will therefore give only two quotations to support this conclusion.

In his second paper of 1900 (previously believed to contain the first statement of the quantum hypothesis) Planck wants to calculate "the distribution of the energy *E* over the *N* [hypothetical] resonators of frequency *v*. If *E* is considered to be a continuously divisible quantity, this distribution is possible in infinitely many ways. We consider, however—this is the most essential point of the calculation—*E* to be composed of a well-defined number of equal parts." He introduces an "energy element" so that "dividing E by *ε* we get the number *P* of energy elements which must be divided over the *N* resonators." So far, it looks like a real quantum hypothesis. But then he adds the sentence: "If the ratio thus calculated is not an integer, we take for *P* an integer in the neighborhood."[18] So Planck was not actually proposing quantization of the resonator energies as a

16. Thomas S. Kuhn (ref. 4) and "Revisiting Planck," *HSPS, 14:2* (1984), 231–242. After much resistance, Kuhn's interpretation has now been generally accepted by historians of physics. Jochen Büttner, Jürgen Renn, and Matthias Schemmel, "Exploring the limits of classical physics: Planck, Einstein, and the structure of a scientific revolution," *Studies in history and philosophy of modern physics, 34B* (2003), 37–59. See also S.G. Brush, "Thomas Kuhn as a historian of science," *Science and education, 9* (2000), 39–58; Cathryn Carson, "The origins of the quantum theory," *Beamline, 30:2* (2000), 6–19; Helge Kragh, "Max Planck: The reluctant revolutionary," *Physics world*, *13:12* (2000), 31–35; Olivier Darrigol, "Continuities and discontinuities in Planck's *Akt der Verzweiflung," Annalen der Physik* (Leipzig) [series 8], 9 (2000): 851–860; "Quantum theory and atomic structure, 1900–1927," in Mary Jo Nye, ed., *The Cambridge history of science*, vol. 5, *The modern physical and mathematical sciences*, 331–349 (New York, 2003).
17. See ref. 5.
18. Max Planck, "Zur Theorie des Gesetzes der Energieverteilung im Normalspectrum," *Verhandlungen der Deutschen Physikalisch Gesellschaft, 2* (1900), 237–245. See *Planck's original papers in quantum physics, German and English edition*, ann. Hans Kangro, trans. D. ter Haar and Stephen G. Brush (London, 1972), 8, 10–11, 40, 42–43, 54–55, quote on 40. As Olivier Darrigol points out, the last sentence "leaves no reason for doubt": "the energy of a single resonator was not thought to be restricted to multiples of *ε*." See *From c-numbers to q-numbers: The classical analogy in the history of quantum theory* (Berkeley, 1992), 73.

physical hypothesis, but only as a mathematical approximation to allow the use of a combinatorial formula for *W*: the number of ways of distributing something must be an integer.[19]

As late as 1910, Planck refused to accept Einstein's hypothesis that electromagnetic radiation is quantized. Planck warned that one should not be so hasty in throwing out the wave theory of light, after all the struggles to establish it and all its successes in explaining and predicting so many phenomena. He still believed in the strict validity of Maxwell's equations for empty space, thus excluding the possibility of discrete energy quanta in a vacuum.[20]

In his Nobel lecture, Planck declined credit for the physical quantum hypothesis. Discussing the introduction of the constant *h*, he said it could be explained in two ways. It might be just a "fictitious quantity, in which case all the deductions from the radiation theory were largely illusory and were nothing more than mathematical juggling." Alternatively one could assume that "the radiation theory is founded on actual physical ideas . . . something quite new" replacing the "assumption of continuity of all causal relations." *Which was it to be*? To that question Planck gave the answer:[21]

> Experience has decided for the second alternative. That this decision should be made so soon and so certainly is not due to the verification of the law of distribution of energy in [black-body] heat radiation, much less to my special derivation of the law, but to the restless, ever-advancing labour of those workers who have made use of the quantum of action in their investigations.
>
> The first advance in this work was made by A. Einstein. . . .

19. When Planck rewrote and expanded his 1900 papers for publication in 1901, he omitted the statement that if the number of quanta is not an integer one should take the nearest integer ["Ueber das Gesetz der Energieverteilung im Normalspektrum," *Annalen der Physik* [series 4], *4* (1901), 553–563, on 556–557]. Thus if you insist on giving the credit to Planck for originating the quantum theory, your case is a little stronger if you cite his paper of 1901 rather than just the brief announcement of 1900. But we must still consider the following facts, which do not seem to be controversial: (1) Even in the paper of 1901 he never suggested (as Einstein did in 1905) that electromagnetic radiation in space is quantized; his quantum hypothesis, whether physical or mathematical, applies only to the amount of energy possessed by a resonator and to the amount that can be emitted or absorbed. (2) During the next few years he retreated from that position, denying for example that the *absorption* of energy is quantized and suggesting that the resonator in general will possess a non-integer number of quanta. See Kuhn (ref. 4), chapts. 4, 5, and 10; Jagdish Mehra, *The Solvay Conferences on Physics: Aspects of the development of physics since 1911* (Dordrecht, 1975), 24–40.
20. M. Planck, "Zur Theorie der Wärmestrahlung," *Annalen der Physik* [ser. 4], *31* (1910), 758–768. On his changing views see Holton (ref. 4), 156–158; *Collected papers of Albert Einstein, 5* (Princeton, 1995), docs. 47, 303; Planck, *Das Wesen des Lichts* (Berlin, 1920).
21. M. Planck, *Die Entstehung und bisherige Entwicklung der Quantentheorie* [Nobel Prize Lecture] (Leipzig, 1920). Trans. R. Jones and D.H. Williams, in *A survey of physical theory* (New York, 1960), 102–114, on 109.

4. EINSTEIN'S "HEURISTIC VIEWPOINT"

In the publication of 1905 summarized in Section 1, sometimes misleadingly called his "photoelectric effect paper," Einstein proposed the following equation for the maximum kinetic energy of an electron ejected from a solid by a single quantum of energy *h*, assuming that the energy needed to bring it from inside to the surface of the solid is *p:*

$$\frac{1}{2}Mv^2 = h\nu - p$$

(this is the notation used by Millikan and others in the 1910s and later).[22] I will call this "Einstein's photoelectric equation"; it amounts to a *prediction* to be tested by experiment. According to Stuewer, the empirical data available in 1905 were not adequate to confirm it, so it should be regarded as a *novel* prediction in the usual terminology of philosophers of science, or a *prediction in advance* as physicists often say.[23]

Einstein proposed, according to the title of his paper, a "heuristic viewpoint," an exploratory approach intended to uncover new facts without any commitment to a definite theory.[24] He clearly did not want to *replace* the wave theory by a particle theory, although he implied that the wave theory might be derivable from a particle theory. He did not, in 1905, propose what was later called wave-particle duality or complementarity, which requires that waves and particles coexist on the same ontological level; nor did he follow Descartes' strategy, three centuries earlier, of proposing two contradictory hypotheses for the nature of light without apparently believing in the truth of either one. But he did, in a famous letter to Konrad Habicht, call his light quantum hypothesis "very revolutionary," a term he did not use to describe his relativity theory.[25]

22. Albert Einstein (ref. 5), from D. ter Haar's trans. (ref. 5), 91–92.
23. Roger Stuewer, "Non-Einsteinian interpretations of the photoelectric effect," in Stuewer, ed., *Historical and philosophical perspectives of science* (Minneapolis, 1970), 246–263, on 247–248. See also Wheaton (ref. 4), 108.
24. The word comes from a Greek root meaning "discover," more familiar to modern readers from the famous exclamation of Archimedes, "Eureka!" (I have found it). The *Neue Deutsche Wörterbuch*, ed. Lutz MacKenfen (Laupheim, rept. 1953) defines "heuristisch" simply as "erfinderlisch." Einstein's approach seems quite similar to that of J.J. Thomson, as described by McCormmach: a theory should "suggest things which can be tried by experiment, and for this the theory should be one that is easily visualized." Moreover, as Lord Rayleigh noted in his biography of Thomson, this approach means that one stresses "what a theory *would* explain rather than what it would not." Some of the critics of Einstein and Thomson were (as it turned out) overly obsessed with the difficulties of explaining interference and other wave properties by a particle theory. McCormmach (ref. 3), 364.
25. Einstein, letter to Konrad Habicht, 18 or 25 May 1905, in Martin J. Klein, A.J. Kox, and Robert Schulmann eds., *Collected papers of Albert Einstein* (Princeton, 1993), *5*, 31–32, on 31.

Here is Karl K. Darrow's insightful definition of the word "heuristic" as used by Einstein: it seems to[26]

> describe a theory which achieves successes though its author feels at heart that it really is too absurd to be presentable. The implication is, that the experimenters should proceed to verify the predictions based upon the idea quite as if it were acceptable, while remembering always that it is absurd. If the successes continue to mount up, the absurdity may be confidently accepted to fade gradually out of the public mind

This definition could apply to the quantum theory as a whole: it started out as a set of formulae obtained by juggling equations without taking too seriously the physical principles implied by those equations. When the equations gave results in agreement with empirical observations, the physics had to be revised in order to agree with the equations.

In 1916 Einstein published an important paper elaborating his quantum theory of radiation. According to classical electrodynamics, "If a body emits the energy ε, it receives a recoil (momentum) ε/c if all of the radiation ε is emitted in the same direction. If, however, the emission takes place as an isotropic process, for instance, in the form of spherical waves, no recoil at all occurs. . . . *It now turns out that we arrive at a consistent theory only, if we assume each elementary process to be completely directional.*" In particular, "If a ray of light causes a molecule hit by it to absorb or emit through an elementary process an amount of energy $h\nu$ in the form of radiation…the momentum $h\nu/c$ is always transferred to the molecule." The interaction of radiation and matter must conserve momentum as well as energy; a quantum of radiation must have a definite momentum in a particular direction ("There is no emission in spherical waves.") But the recoil of the molecule is "in a direction which is in the present state of the theory determined only by "chance."[27]

5. WHAT DID MILLIKAN PROVE?

During the decade after Einstein proposed his Light Quantum Hypothesis and the photoelectric equation derived from it, empirical evidence gradually accumulated for the equation but the hypothesis was not generally accepted. Physicists argued

26. Karl K. Darrow, *Introduction to contemporary physics* (New York, 1926), 116–117.
27. Einstein (ref. 6). English trans., "On the quantum theory of radiation," in ter Haar (ref. 5), 167–183, on 169 and 182. This paper is also important because it provided the theoretical basis for the "laser" and because Einstein expressed there his unhappiness with the randomness that he himself had introduced into the quantum theory: "The weakness of the theory lies, on the one hand, in the fact that it does not bring any nearer the connexion with the wave theory and, on the other hand, that it leaves [the] moment and direction of the elementary processes to 'chance'" (p. 182).

that Einstein's equation could be just as well explained by other hypotheses that were compatible with the wave theory of light.[28]

Robert A. Millikan provided in 1916 the most definitive experimental proof of the equation; he also found that the value of Planck's constant *h* obtained from his experiments was the same as that deduced from Planck's law of black body radiation. This could be seen as a link between the LQH and the more general quantum theory, which had been successfully applied to the specific heats of solids (Einstein, Debye) and the spectrum of hydrogen (Bohr). Yet he also expressed an uncompromising rejection of the hypothesis from which the photoelectric equation had been derived. He wrote:[29]

> We are confronted . . . by the astonishing situation that [the facts of photoelectric phenomena] were correctly and accurately predicted nine years ago by a form of quantum theory which has now been pretty generally abandoned . . . . The semi-corpuscular theory by which Einstein arrived at this equation seems at present to be wholly untenable.

In his book *The electron* published the next year, he elaborated these statements. The failure to explain interference is a "very potent objection" to Einstein's and similar theories; J.J. Thomson's theory, which seemed to offer the best hope of accounting for the apparently-corpuscular properties of radiation by assuming that "the energy remains localized in space instead of spreading over the entire wave-front," had the fatal defect that it relied on the ether having a "fibrous structure," which Millikan's oil-drop experiment disproved.[30] Lenard's "trigger" theory had some advantages but, he believed, was still unsatisfactory.[31] He concluded:[32]

28. Stuewer (ref. 23). Thomas S. Kuhn, "Foreword" in Wheaton (ref. 4), ix–xiii, on ix. Hermann (ref. 4).
29. Millikan, "Direct photoelectric determination" (ref. 8), 355, 383. The view that Millikan's work was the "most definitive" is now accepted, but A.H. Compton stated, on the contrary, that the experiment his older brother Karl did with Richardson was the most important. Owen W. Richardson and Karl T. Compton, "The photoelectric effect," *Philosophical magazine, 24* (1912), 575–594. See A.H. Compton, *X-rays and electrons* (New York, 1926), 223; "Michelson, Millikan, and Richardson" [1931], in M. Johnston ed., *The cosmos of Arthur Holly Compton*, (New York, 1967), 193–201, on 200. G.E.M. Jauncey, *Modern physics* (New York, 1932, 8th printing 1935), 204–205. Robert W. Wood, *Physical optics* (3rd edn., New York, 1934), 764.
30. Millikan, *The electron* (ref. 8), 221–230.
31. Ibid., 31. Philipp Lenard, "Über die lichtelektrische Wirkung," *Annalen der Physik, 8* (1902), 149–198. Bruce R. Wheaton, "Philipp Lenard and the photoelectric effect, 1889–1911," *HSPS, 9* (1978), 299–322.
32. Millikan, *The electron* (ref. 8), 238. See also Holton (ref. 4). For an account of Millikan's work with students on the photoelectric effect see John L. Michel, "The Chicago connection: Michelson and Millikan, 1894–1921," in Stanley Goldberg and Roger H. Stuewer eds., *The Michelson era in American science 1870–1930*, (New York, 1988), 152–176. Millikan's coupling of Thomson's and Einstein's theories now seems inappropriate, but reflects the attitude of many physicists at that time who were more interested in the general question (wave versus particle nature of light) than in the difference between alternative particle theories (see below Section 7).

> We seem to be driven . . . either to the Thomson-Einstein semi-corpuscular theory, or else to a theory which is equally subversive of the established order of things in physics. . . . To be living in a period which faces such a complete reconstruction of our notions . . . is an inspiring prospect.

Either way we will have “a very revolutionary quantum theory of radiation.”

Millikan has been criticized for refusing to accept the light-quantum hypothesis that his own experiments confirmed, and some historians have tried to explain his puzzling behavior.[33] But was it really so puzzling? From a logical point of view (and this was an argument strongly emphasized by the philosopher Karl Popper), an experiment cannot *confirm* a hypothesis, unless you can prove that no other hypothesis could lead to the same empirical result. In this case there were indeed several other hypothesis that could explain Einstein’s equation. More importantly, it does not make sense to abandon a hypothesis like the wave theory of light, which made several confirmed predictions and explained most of the observable properties of light, in favor of a hypothesis that is credited with only one confirmed prediction, along with plausible explanations of a few other phenomena, but *fails* (as of 1916) to explain wave properties like interference, or the fact that light travels faster in a less dense medium. Isn’t it unreasonable to fault Millikan for refusing to accept what we *now* consider to be the “right answer” even though some of the best evidence for the LQH had not yet been uncovered in 1916?[34]

Einstein received the Nobel Prize in 1921. Physicists are often surprised to learn that he did not get it for relativity but for quantum theory. With the recent recognition by historians that Einstein rather than Planck was the originator of the *physical* quantum hypothesis (see above, section 3), the decision of the Nobel Prize electors makes a little more sense. But why would they give him the prize for a theory that was not yet accepted?

The answer is, they didn’t. Although the original draft citation mentioned Einstein’s *theory* of the photoelectric effect, it was changed to Einstein’s *equation*.[35]

33. Giora Hon, “Towards a typology of experimental errors: An epistemological view,” *Studies in history and philosophy of science, 20* (1989), 469–504, on 496–497.

34. That does not of course excuse Millikan for misrepresenting his views of 1916 in his autobiography in order to claim more credit than he deserves for establishing the particle nature of light. See Stuewer, *Compton effect* (ref. 4), 88, note 125 and “Experimental challenge” (ref. 4); Gerald Holton, “R.A. Millikan’s struggle with the meaning of Planck’s constant,” *Physics in perspective, 1* (1999), 231–237.

35. The citation reads: “for his services to theoretical physics and especially for his discovery of the law of the photoelectric effect.” In his presentation speech, Svante Arrhenius mentions Millikan’s experimental confirmation of Einstein’s equation but does not explicitly say that this means the theory from which the equation was derived is valid. He does praise the quantum theory in general, and its application to the specific heats of solids as well as to the photoelectric effect: “Owing to these studies by Einstein the quantum theory has been perfected to a high degree and an extensive literature grew up in

To have discovered the quantitative nature of the phenomenon was important enough to deserve the prize even if the discovery was made with the help of a dubious theory![36]

6. THE COMPTON EFFECT

Between 1905 and 1922, other empirical evidence both for and against the Light Quantum Hypothesis emerged. In addition to the large amount of research on the photoelectric effect, Eddington's announcement that he had confirmed Einstein's light-bending prediction gave more credibility to the latter's assertion that the luminiferous ether is unnecessary (and its putative properties are even more implausible than they seemed in the 19th century). Hence, proponents of "light waves" could not rely on a material medium to propagate those waves, a difficulty not faced by corpuscularists. Moreover, the fact that gravity can act on light is easy to understand if light consists of particles that have mass, but mystifying if light is simply a wave motion. (The light quantum does not have mass in the ordinary sense but does have an "effective mass" determined by its frequency.)

On the other hand G.I. Taylor, in an attempt to test J.J. Thomson's theory, obtained in 1909 an experimental result that seemed to refute not just Thomson's but all other corpuscular theories. Thomson had proposed that the wave front in a ray of light is not uniform but "speckled" with small regions of high intensity. "When the intensity of light is reduced these regions become more widely separated but the amount of energy in any one of them does not change; that is,

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this field whereby the extraordinary value of this theory was proved." See "The general and present state of development of the quantum theory," in *Nobel lectures . . . physics 1901–1921* (Amsterdam, 1967), 477–481. For details see Robert Marc Friedman, "Text, context, and quicksand: Method and understanding in studying the Nobel science prizes," *HSPS, 20:1* (1989), 63–77, and *The politics of excellence: Beyond the Nobel Prize in science* (New York, 2001), chapt. 7. Abraham Pais, "How Einstein got the Nobel Prize," *American scientist, 70* (1982), 358–365.

36. Millikan received the Nobel Prize for 1923, in part for his confirmation of Einstein's photoelectric equation. In his lecture, delivered 23 May 1924, he said: "the general validity of Einstein's equation is, I think, now universally conceded, and *to that extent the reality of Einstein's light quanta may be considered as experimentally established*. But the conception of *localized* light-quanta out of which Einstein got his equation must still be regarded as far from being established." *Nobel lectures . . . physics*, vol. 2, 54–66. In the second edition of his book *The electron* (Chicago, 1924), completed around the same time, he acknowledged that the phenomenon discovered by A.H. Compton "constitutes the best evidence yet found in favor of Einstein's hypothesis of localized light-quanta" but despite its many successes "the theory is as yet woefully incomplete and hazy. About all that we can say now is that we seem to be driven by newly discovered relations in the field of radiation to the hypothetical use of a fascinating conception which we cannot as yet reconcile at all with well-established wave-phenomena" (pp. 256–260).

they are indivisible units." If the intensity of light in a diffraction pattern "were so greatly reduced that only a few of these indivisible units of energy should occur in a Huygens zone at once the ordinary phenomena of diffraction would be modified." Taking photographs with long exposure time (up to 3 months), Taylor found "In no case was there any diminution in the sharpness of the pattern." This sets an upper limit of 1.6×10^{-16} ergs to the amount of energy in one of the indivisible units.[37]

A decade later, A.A. Michelson found a way to use his interferometer to measure the diameter of a giant star. On December 13, 1920, using a 20-foot interferometer, Michelson and F.G. Pease were able to estimate that the diameter of α Orionis (commonly known as Betelgeuse) is about 240 million miles.[38] Lorentz and others saw this result as a refutation of the LQH, since according to Einstein's hypothesis, a quantum would have to be 20 feet long in order to reach from one of the outer mirrors to the other, yet at the same time "small enough to be captured by a single electron."[39]

As Roger Stuewer described in detail in 1971, the establishment of the corpuscular nature of electromagnetic radiation in the 1920s was not simply the outcome of research on black body radiation and the photoelectric effect; instead it owed much to the study of x- and gamma rays.[40] Many of the x-ray phenomena were most easily explained, by G.G. Stokes and others, by assuming that the rays consisted of localized "pulses" rather than continuously-extended waves. It was observed that

37. G.I. Taylor, "Interference fringes with feeble light," Cambridge Philosophical Society, *Proceedings, 15* (1909), 114–115. In recalling this experiment 54 years later, Taylor wrote that it was his first research experience after taking his degree at Cambridge; it was suggested by Thomson, but Taylor described it as a test of the idea that "light consists of spots or quanta of energy localized in space" without mentioning Einstein or noting that he was testing Thomson's own theory. "Scientific diversions," in S.W. Higginbotham ed., *Man, science, learning and education*, (Houston, 1963), 137–148, quoted in G. Batchelor, *The life and legacy of G.I. Taylor* (Cambridge, UK, 1996), 40–41. See also McCormmach (ref. 3), 369.
38. Albert A. Michelson, "On the application of interference methods to astronomical measurements," *Astrophysical journal, 51* (1920), 257–262. Michelson and F.G. Pease, "Measurement of the diameter of α Orionis with the interferometer," *Astrophysical journal, 53* (1921), 249–259.
39. H.A. Lorentz, "The radiation of light" (lecture at the Royal Institution of Great Britain, 1 June 1923), *Nature, 113* (1924), 608–611; *Collected papers*, vol. 8, 17–27. Karl K. Darrow (ref. 26), 162. Paul R. Heyl, *The fundamental concepts of physics in the light of modern discovery* (Baltimore, 1926), 80.
40. Roger H. Stuewer, "William H. Bragg's corpuscular theory of x-rays and γ-rays," *The British journal for the history of science, 5* (1971), 258–281; Stuewer, *Compton effect* (ref. 4); Wheaton (ref. 4). According to T.S. Kuhn, "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 1900, five years after their discovery, x-rays were almost everywhere assumed to be particulate." T.S. Kuhn, "Foreword," in Wheaton (ref. 4), ix–x.

when x-rays were scattered from matter, some of the "secondary" scattered rays were "softer" (less penetrating) than the primary rays. In 1921, before he had adopted the corpuscular hypothesis himself, Arthur Holly Compton mentioned this explanation as proposed by the Canadian physicist Joseph Alexander Gray:[41]

> Prof. J. A. Gray (*Franklin Institute Journal*, November, 1920) . . . showed that if the primary rays came in thin pulses, as suggested by Stokes's theory of x-rays, and if these rays are scattered by atoms or electrons of dimensions comparable with the thickness of the pulse, the thickness of the scattered pulse will be greater than that of the incident pulse. He accordingly suggests that the observed softening of the secondary rays may be due to the process of scattering.

Compton believed that his own data refuted Gray's hypothesis; at that time he was trying several other ways to explain the data, without yet having settled on any particular theory.[42] But during the following year he decided that a somewhat different explanation, the light-quantum hypothesis, might be valid. He credited O.W. Richardson[43] for the idea "that as the electron absorbs a quantum $h\nu$ of energy, the momentum of the absorbed radiation is also transferred to the electron. . . ." But Compton then explicitly rejected that idea.[44]

In May 1923 Compton published a 20-page paper in *The physical review* laying out his theory of the scattering of x-rays by electrons, with supporting experimental data. The essence of the "Compton effect," as this kind of scattering quickly came to be called, is that one can calculate both the change in wave-length of the scattered x-ray and the momentum of the "recoil electron" by treating both as particles with specified energy and momentum, each of these two quantities (summed over all particles) being conserved in the collision. The increase in wavelength of the x-ray is a simple function of the angle between the incident and scattered ray: $\Delta\lambda = (2h/mc) \sin^2 (\frac{1}{2}\theta)$, independent of the wave-length. Moreover,[45]

41. A.H. Compton, "The softening of secondary x-rays," *Nature, 108* (1921), 366–367, on 366. Stuewer, *Compton effect* (ref. 4).
42. "The mistaken notion is to get some idea and then try to prove it. . . . The real thing that a scientist tries to do when he is faced with a phenomenon is to attempt to understand it. To do that he tries all the possible answers that he can think of to see which of them works best."—Arthur Holly Compton, quoted by Stuewer (ref. 4), 96, from *Cosmos* (ref. 29), 23.
43. O.W. Richardson, "The asymmetric emission of secondary rays," *Philosophical magazine, 25* (1913), 144–150. *The electron theory of matter* (Cambridge, UK, 1914), 478–481. But he argued that it followed directly from Planck's black-body law, not from Einstein's theory.
44. A.H. Compton, "Secondary radiation produced by x-rays, and some of their applications to physical problems," *Bulletin of the National Research Council, 4*, pt 2, no. 20 (1922), 24. Robert S. Shankland, ed., *Scientific papers of Arthur Holly Compton: X-ray and other studies* (Chicago, 1973), 382–401. On the origin of Compton's formula $p = E/c$ for the momentum of a light quantum, see R. S. Shankland, appendix 1 in ibid*.,* 756–758.
45. A.H. Compton, "A quantum theory of the scattering of x-rays by light elements," *Physical review* [series 2], *21* (1923), 483–502; Shankland (ref. 44). The same theory was developed

> Any particular quantum of x-rays is not scattered by all the electrons in the radiator, but spends all of its energy upon some particular electron. This electron will in turn scatter the ray in some definite direction, at an angle with the incident beam. This bending of the path of the quantum of radiation results in a change in its momentum. As a consequence, the scattering electron will recoil with a momentum equal to the change in momentum of the x-ray.

According to Compton, "the electrons which recoil in the process of the scattering of ordinary x-rays have not been observed."[46] Within two months of the publication of Compton's paper, C.T.R. Wilson reported the observation of these recoil electrons, using his new "cloud chamber" method. Compton immediately pointed out that Wilson's observation confirmed his prediction.[47] Similar results were reported by Bothe[48] and by Compton and J.C. Hubbard.[49]

Compton now began a campaign to prove that his effect provided stronger evidence for the light-quantum hypothesis than did the photoelectric effect. In addition to the fact that the Compton effect confirms the conservation of momentum as well as energy while the photoelectric effect involves only energy, he argued that his theory produced a confirmed *novel prediction* (in the terminology now used by philosophers of science), the existence and properties of *recoil electrons*, whereas Einstein's photoelectric hypothesis did not:[50]

> In view of the fact that these recoil electrons were unknown at the time this theory was presented, their existence and the close agreement with the predictions as to their number, direction and velocity supplies strong evidence in favor of the fundamental hypotheses of the quantum theory of scattering,

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by Peter Debye, "Zerstreuung von Röntgenstrahlung und Quantentheorie," *Physikalische Zeitschrift, 24* (1923), 161–166; see Stuewer, *Compton effect* (ref. 2), 234–237, 485. Debye's paper was submitted later but published earlier. According to Max Dresden, Hendrik A. Kramers had worked out the theory in 1921 but Bohr talked him out of publishing it and persuaded him to reject the LQH; see Dresden, *H.A. Kramers: Between tradition & revolution* (New York, 1987), chapt. 14. I thank Roger Stuewer for this reference.

46. Compton (ref. 45), 496.

47. Charles T.R. Wilson, "Investigations on x-rays and -rays by the cloud method," *Nature, 112* (1923), 26–27; "Investigations on x-rays and γ-rays by the cloud method. Part I.-x-rays," Royal Society of London, *Proceedings, 104* (1923), 1–24. A.H. Compton, "Recoil of electrons from scattered x-rays," *Nature, 112* (1923), 435. Wilson, "Recoil of electrons from scattered x-rays," *Nature, 112* (1923), 435.

48. Walther Bothe, "Über neue Sekundärstrahlung der Röntgenstrahlen. I. Mitteilung," *Zeitschrift für Physik, 16* (1923), 319–320; ". . . II. Mitteilung," *Zeitschrift für Physik, 20* (1924), 237–255.

49. A.H. Compton and J.C. Hubbard, "The recoil of electrons from scattered x-rays," *Physical review, 23* (1924), 439–449.

50. A.H. Compton, "The scattering of x-rays," *Journal of the Franklin Institute, 198* (Jul 1924), 57–72, on 68.

The stakes were high; if electromagnetic radiation behaves like particles, that would undermine the century-long dominance of the wave theory of light; his experiments show[51]

> that x-rays, and so also light, consist of discrete units, proceeding in definite directions, each unit possessing the energy $h\nu$ and the corresponding momentum h/λ. So in a recent letter to me Sommerfeld has expressed his opinion that the discovery of the change of wave-length of radiation, due to scattering, sounds the death knell of the wave theory of radiation.

In a popular article, Compton reviewed the evidence that the wave theory of light should be revised. Einstein was credited with reviving "the old Newtonian idea of light corpuscles" in the form of quanta, but

> since the idea of light quanta was invented primarily to explain the photoelectric effect, the fact that it does so very well is no great evidence in its favor. The wave theory explains so satisfactorily such things as the reflection, refraction and interference of light that the rival quantum theory could not be given much credence unless it was found to account for some new theory for which it had not been especially designed. This is just what the quantum theory has recently accomplished in connection with the scattering of x-rays.

The wave theory, Compton pointed out, predicts that scattered x-rays will have the same wavelength as the primary (incident) rays. Quantum theory explains why some of them have longer wavelengths and predicts the existence of recoil electrons, later discovered by Wilson and confirmed by Compton's group, which also found that the number of cloud chamber tracks, their direction and range agree with the predictions of quantum theory.[52]

51. Ibid., p. 70.
52. A.H. Compton, "Light waves or light bullets?" *Scientific American*, *133* (Oct 1925), 246–247. According to Roger Stuewer (private communication), Compton's statement that Einstein invented the LQH "primarily to explain the photoelectric effect" is clear proof that he never read Einstein's 1905 paper.

A note on terminology: The word "photon" for light quantum was first introduced in print by Gilbert N. Lewis in 1926, and therefore is not appropriate when discussing the earlier period. (It was suggested in private in a letter from Richard Swinne to Einstein, 12 Feb 1912; see *Collected papers of Albert Einstein,* (Princeton, 1995), *5*, doc. 253.) When the light quantum was finally accepted as a real particle, it deserved a name similar to those of the other real particles, electrons and protons. G.N. Lewis, "The conservation of photons," *Nature, 118* (1926), 874–875. See also E.S. Lewis, *A biography of distinguished scientist Gilbert Newton Lewis* (Lewiston, NY, 1998), 46, on his father's views on photons at that time and their criticism by Einstein, and Arthur Lachman, *Borderland of the unknown: The life story of Gilbert Newton Lewis, one of the world's great scientists* (New York, 1955), 114–118. Some of Lewis's views, which seemed bizarre at the time, are now accepted by mainstream physicists.

> Since their very existence was unknown before they were predicted by the quantum theory, these recoil electrons must be taken as a strong support of the theory of radiation quanta.

In a paper in *Physical review*, Compton stated his claim in a different way: there are now several phenomena most simply explained by Einstein's LQH, but none that "necessarily demand" it. Thus the photoelectric effect can be explained by wave theory if you postulate a mechanism inside the atom to store energy until a quantum is received. But non-corpuscular explanations of the Compton effect, while possible, are not plausible.[53]

This argument was apparently not very convincing, so Compton went back, in three later publications, to his previous assertion that the discovery of recoil electrons confirmed a novel prediction whereas Einstein's LQH merely explained known facts and thus was not as strong evidence as that from the Compton effect.[54] The denigration of the photoelectric effect was somewhat unfair, since according to Stuewer, "Einstein's light quantum hypothesis . . . was . . . a necessary consequence of very fundamental assumptions: in no sense did he propose it in an ad hoc fashion to 'explain' certain experiments. . . . [His] prediction that the maximum photoelectron energy depends linearly on the frequency of the incident radiation" was bold since "the experimental situation was highly uncertain," and other (non-linear) relations were being proposed. McCormmach argues that Einstein's theory was more successful in winning support than Thomson's largely because the former made quantitative predictions while the latter did not.[55] Moreover, Millikan also found that the constant *h* in the photoelectric equation has the *same numerical value* as that deduced from other phenomena such as black body radiation.

But Compton might have been correct in thinking that a prediction of a qualitatively new phenomenon (recoil electrons) would count as better evidence than the quantitative refinement of a qualitatively known phenomenon. From my viewpoint the relevant question (especially for those who want to know whether novel predictions are better evidence than retrodictions) is: did other physicists accept Compton's claim about recoil electrons?

Two physicists who clearly did not accept that claim were Niels Bohr and H.A. Kramers. They were so desperate to rescue the wave theory of light that they were

53. A.H. Compton and A.W. Simon, "Directed quanta of scattered x-rays," *Physical review, 26* (1925), 289–299.
54. A.H. Compton, "Some experimental difficulties with the electromagnetic theory of radiation," *Journal of the Franklin Institute, 205* (1928), 155–178; "The corpuscular properties of light," *Physical review supplement [=Reviews of modern physics], 1* (1929), 74–89; "What things are made of—II," *Scientific American, 140* (Mar 1929), 234–236.
55. R.H. Stuewer (ref. 23), 247–248. R. Pohl and P. Pringsheim, "On the long-wave limits of the normal photoelectric effect," *Philosophical magazine [series 6], 26* (1913), 1017–1024. A.L. Hughes and L.A. DuBridge, *Photoelectric phenomena* (New York, 1932), 8. Helge Kragh agrees that it was a "truly novel prediction" in (ref. 4), 67. See also McCormmach (ref. 3), 371–372.

willing to give up the absolute validity of the laws of conservation of energy and momentum in interactions between x-rays and electrons. Following a suggestion of C.G. Darwin and with the somewhat reluctant assistance of John C. Slater, they developed a theory that reduced those laws to statistical averages, denying a direct causal connection between the incident x-rays and the scattered x-rays and electrons.[56] Their theory disgusted Einstein so much that he exclaimed, in a famous statement whose context is often forgotten, that if it were true he would rather be a cobbler than a physicist.[57] This is a precursor of his even more famous assertion, "God does not play dice."

This new attack on the LQH, called the "Copenhagen Putsch" by Wolfgang Pauli,[58] yielded a new novel prediction that could be directly tested. The test was conducted by Bothe and Geiger and by Compton and Simon; both groups concluded that the Bohr-Kramers-Slater theory was wrong, and reconfirmed the reality of light quanta.[59] Pauli was delighted by this turn of events.[60] Bohr abandoned his opposition to the LQH[61] and invented a concept, "complementarity," to explain how

56. N. Bohr, H.A. Kramers, and J.C. Slater, "The quantum theory of radiation," *Philosophical magazine [series 6], 47* (1924), 785–802. See the extensive commentary and documentation on this paper in *Niels Bohr collected works, 5*, ed. K. Stolzenburg (Amsterdam, 1984), 99–118. Neil Henry Wasserman, *The Bohr-Kramers-Slater paper and the development of the quantum theory of radiation in the work of Niels Bohr* (Ph.D. dissertation, Harvard University, 1981); Mara Beller, *The genesis of interpretations of quantum physics 1925–1927* (Ph.D. dissertation, University of Maryland, 1983), chapt. 4, and *Quantum dialogue* (Chicago, 1999); J.C. Slater, "The development of quantum mechanics in the period 1924–1926," in W.C. Price et al., eds., *Wave mechanics: The first fifty years* (New York, 1973), 19–25; Slater, *Solid state and molecular theory—A scientific autobiography* (New York, 1975).
57. Letter from Albert Einstein to Hedwig and Max Born, 29 Apr 1924, in Max Born, ed., *The Born-Einstein letters* (New York, 1971), 82; see also *Physics today, 58:11* (Nov 2005), 14. For an account of Einstein's objections to the Bohr-Kramers-Slater theory see Wolfgang Pauli, letter to Bohr, 2 Oct 1924, in *Niels Bohr collected works*,(ref. 56), *5,* 414–418; English trans., ibid., 414–418; English trans., ibid., 418–421.
58. Pauli, letter to Kramers, 27 Jul 1925, in ref. 13, 439–442; English trans., ibid., 442–444.
59. W. Bothe and K. Geiger, "Über das Wesen des Comptoneffekts: ein experimenteller Beitrag zur Theorie der Strahlung," *Zeitschrift für Physik, 32* (1925), 639–663. A.H. Compton and A.W. Simon (ref. 53).
60. Pauli (ref. 58).
61. Bohr, Jul 1925 "Nachschrift" at the end of his paper "Über die Wirkung von Atomen bei Stössen," *Zeitschrift für Physik, 34* (1925), 142–157; Stolzenberg, ed. (ref. 56), 178–193; English trans., ibid., 194–206. The result of the Bothe-Geiger experiment "forces upon us the picture of a corpuscular propagation of light corresponding to *Einstein*'s theory of light quanta." Yet in private correspondence he was already beginning to withdraw this concession. In a letter to Geiger (21 Apr 1925), replying to the news of the results of Bothe and Geiger, he suggests the need to abandon "the ordinary space-time description of phenomena" and that "conclusions about a possible corpuscular nature of radiation lack a sufficient basis." Ibid., 353–354, English trans. in Stolzenburg's commentary, ibid., p. 79. In 1929 he wrote: "in accordance with the classical electromagnetic conceptions we cannot,

(or rather, assert that) pairs of apparently incompatible concepts such as waves and particles can both be valid at the same time.[62]

Compton and Wilson shared the 1927 Nobel Prize in physics. One might think this award completed the triumph of the LQH. But the award to Compton was not for "establishing the particle character of electromagnetic radiation" but simply "for his discovery of the effect named after him." And Compton was, at least for a few minutes, robbed of his triumph by another putsch, this one engineered by Erwin Schrödinger. In the presentation speech, Manne Siegbahn stated: [63]

> Compton deduced a new kind of corpuscular theory, with which all experimental results showed perfect agreement within the limit of experimental error. . . . This theory predicts recoil electrons. . . . It was a triumph for both parties [Compton and Wilson] when these recoil electrons were discovered by Wilson's experimental method both by Wilson himself and, independently, by another investigator. Hereby the second chief phenomenon of the Compton effect was experimentally verified [the first was the change in wavelength of the scattered x-rays], and all observations proved to agree with what had been predicted in Compton's theory. . . . The Compton effect has, through the latest evolutions of the atomic theory, *got rid of the original explanation based upon a corpuscular theory. The new wave mechanics, in fact, lead as a logical consequence to the mathematical basis of Compton's theory.* Thus the effect has gained an acceptable connection with other observations in the sphere of radiation. . . . [emphasis added]

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however, ascribe any proper material nature to light, since observation of light phenomena always depends on a transfer of energy and momentum to material particles. The tangible content of the idea of light quanta is limited, rather, to the account which it enables us to make of the conservation of energy and momentum." Bohr, *The philosophical writings of Niels Bohr, 1* (Cambridge, England, 1934), 113. Bohr's continuing opposition to the LQH and his hope that it can be avoided with the help of Louis de Broglie's wave theory of matter are discussed by Mara Beller, "The birth of Bohr's complementarity," *Studies in history and philosophy of science, 23* (1992), 147–180, and *Quantum dialogue* (ref. 56), p. 134. See also Slater, "Development" (ref. 56) and John Stachel, discussion remark in H. Woolf, ed., *Some strangeness in the proportion* (Reading, MA, 1980), 196.

62. Bohr, "The quantum postulate and the recent development of atomic theory," *Atti del Congresso Internatazionale dei Fisici 11–20 Settembre 1927, Como-Pavia-Roma, 2* (Bologna, 1928), 565–588; *Niels Bohr collected works, 6*, ed. J. Kalckar (Amsterdam, 1985), 113–136. Stuewer (ref. 2), 328–333, summarizes Bohr's view and the reaction of other physicists to it. In her *Quantum dialogue* (ref. 56), 8, Beller writes that this famous "Como lecture" is "considered one of the most incomprehensible texts in twentieth-century physics" and devotes a substantial part of her book to explicating it. Here I note merely that Bohr appears to be accepting the particle nature of light as needed to explain the Compton effect, all doubts having been "disproved by recent experiments" (*Niels Bohr collected works, 6*, 115) yet manages to fudge that concession in the rest of the lecture.

63. Manne Siegbahn, in *Nobel lectures in physics 1922–1941* (Amsterdam, 1964), 169–173. Erwin Schrödinger, "Über den Comptoneffekt," *Annalen der Physik [series 4], 82* (1927), 257–264. G. Ekspong, "The Klein-Nishina formula," in Gösta Ekspong, ed., *The Oskar Klein Memorial Lectures* (Teaneck, NJ, 1994), *2,* 97–112. Brown, "Compton effect," (ref. 2).

Of course Compton, in his acceptance speech, made it quite clear that his discovery was, indeed, that "all electromagnetic radiation is constituted of discrete quanta proceeding in definite directions."[64] For most physicists, this became an established fact, and the only remaining question was how much credit Compton should receive for establishing it. But for a few, the apparent particle behavior of radiation could be reduced to its true wave nature in accordance with Schrödinger's theory[65] or, for more dogmatic anti-realists, the wave-particle controversy itself could be declared a non-issue.[66]

7. RECEPTION OF NEO-NEWTONIAN OPTICS BEFORE 1923

In 1918 Einstein wrote to Besso: "I no longer have doubts about the *reality* of light quanta—even though I'm still quite alone in this conviction." More recently, seven well-known historians of physics—Martin Klein, Helge Kragh, Thomas Kuhn, Jagdish Mehra, Abraham Pais, Helmut Rechenberg, and Roger Stuewer—stated that most or nearly all physicists rejected the Light Quantum Hypothesis before the discovery of the Compton effect. Einstein and the historians may well be correct, but I wish they had provided a little more evidence to support this assertion. Max Planck's opinion that Einstein had "missed the target" in some of his speculations, in particular his LQH, is often quoted, but does not necessarily represent the consensus of the physics community.[67] By contrast, Jungnickel and McCormmach made a more limited claim (quoted in Section 1): that "Planck, Laue, Wien, Sommerfeld and other early supporters of Einstein's relativity theory" rejected the hypothesis; and, more

64. Compton, "X-rays as a branch of optics" (Nobel lecture, 12 Dec 1927); in Shankland (ref. 44), 541.
65. Owen W. Richardson, "On the present state of atomic physics [Presidential address]," Physical Society of London, *Proceedings, 39* (1927), 171–186. Otto Halpern and Hans Thirring, *The elements of the new quantum mechanics* (London, 1932), 140–141.
66. Percy W. Bridgman, *The logic of modern physics* (New York, 1927), 153. Paul A.M. Dirac, *The principles of quantum mechanics* (Oxford, 1930), 7. Joseph Valasek, *Elements of optics* (2nd edn., New York, 1932), 229–230.
67. Einstein, letter to M. Besso, 29 Jul 1918, in *Collected papers of Albert Einstein*, vol. 8, doc. 59; M.J. Klein, "Einstein's first paper on quanta," *The natural philosopher, 2* (1963), 57–96, on 79; "First phase" (ref. 3), 6; "No firm foundations: Einstein and the early quantum theory," in *Some strangeness* (ref. 61), 161–185 and reply to H.D Smyth on p. 193. Kragh (ref. 4), 68. Kuhn (ref. 4), 182. Mehra and Rechenberg (ref. 4, vol. 1), 511. Abraham Pais, "Einstein and the quantum theory," *Reviews of modern physics, 51* (1979), 863–914, on 883–886; *'Subtle is the Lord…': The science and the life of Albert Einstein* (Oxford, 1982); "Einstein on particles, fields and the quantum theory," in *Some strangeness* (ref. 61), 197. Stuewer, *Compton effect* (ref. 4), 23–24, 31, 35, 37, 47, 217–219, 222 (with references to views of W.H. Bragg, J. Stark and others at the 1909 Salzburg meeting, Sommerfeld, Nagaoka, Kaye, Florance, Gray, Compton, Schrödinger, Bohr.) A less extreme statement was made by Armin Hermann, *The genesis of quantum theory* (Cambridge, 1971), 56–57, 62. Planck's criticism, clearly not intended as a damning one, appears in a recommendation

importantly, these historians backed up their claim with specific references to the writings of the four named physicists.[68]

Why do we want to know who the opponents as well as the supporters of the LQH were? First, in order to judge the claim that the LQH was not accepted until after the discovery of the Compton effect. Second, in order to confirm that those physicists who did accept it after 1923 did so because of the evidence from the Compton effect, and to determine how much the confirmation of Einstein's photoelectric equation also counted. I recognize that questions of the type "was X accepted at time T? Why?" cannot be answered simply by counting votes on each side, since some votes are obviously more important than others (and will have a greater influence on other voters). I am not going to propose a definitive answer based on my own estimate of the importance of early-20th century physicists, but will leave that to the judgment of readers. However, I do think it is possible to confirm or refute the statement that "nearly all physicists did *not* accept X during a time interval from T_a to T_b" by examining a reasonably large sample of publications during that interval. In my experience it is more effective to focus on monographs, review articles, and textbooks than on research articles, because the former are more likely to make statements about the nature of light and give reasons for those statements.

Of course we also want to know about the early support for Einstein's theory, even if it came from a minority of physicists. One of the first challenges to the historiographic consensus came from a Russian philosopher, Rinat H. Nugayev. Nugayev disputed the views of Klein and Pais expressed at an Einstein centennial meeting, pointing out that they had been challenged by two physicists who described their own experiences in the 1910s, H.D. Smyth and Walther Gerlach. Smyth recalled that the particle nature of light was accepted at Princeton in 1918/9, while Gerlach remembered that the discovery of x-ray diffraction "enlivened the discussion about Einstein's light quantum theory."[69]

A recollection that reinforces Smyth's but was published much closer to the time was that of Karl K. Darrow, a physicist who was active in popularizing the quantum theory in the 1920s and 1930s. Darrow wrote in 1937:[70]

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by Planck, Nernst, Rubens and Warburg that Einstein should be appointed to the Prussian Academy of Sciences. See the proposal for Einstein's membership in the Prussian Academy of Science, 12 June 1913, in *Collected papers of Albert Einstein* (Princeton, 1995), *5*, doc. 445.

68. Jungnickel and McCormmach (ref. 3), *2*, 305.

69. R.M. Nugayev, *Reconstruction of mature theory change: A theory-change model* (Frankfurt, 1999). 193; Gerlach, "Reminiscences of Albert Einstein from 1908 to 1930," in *Some strangeness* (ref. 61), *Albert Einstein: His influence on physics, philosophy, politics*, eds. P.C. Aichelburg and R. U. Sexl (Wiesbaden, 1979), 189–200, on 191. Nugayev also cites several papers by American scientists in the early 1910s on the "emission theory of light" but most of these deal with the hypothesis that the speed of light depends on the motion of its source, not the particulate nature of light. On the relation between these theories see Stachel (ref. 4), 240.

70. Darrow, *The renaissance of physics* (New York, 1937), 177–178.

> For anyone who studied physics in the years just before the war . . . [the photoelectric effect] was the *pièce de conviction*, the grand piece of evidence which undeniably spoke for the corpuscular nature of light. . . . How enthusiastically our teachers used to speak of it! How strongly they used to stress those of its features which harmonized with the corpuscular theory of light, but apparently not with the undulatory.

Historian Alexei Kojevnikov argues that there was

> a general change of attitude in physics following the end of World War I. . . . By 1920 light quanta grew out of oblivion into an extremely popular concept and began to be widely understood as particles or corpuscles. Traditional historiography saw the explanation of this change in the discovery of the Compton effect in 1923, but the development had already been in place for several years before that and was crowned by, rather than caused by, Compton's landmark achievement. . . . Rather than being caused by new experimental or theoretical developments, the revival of light quanta appears more like a shift in the prevailing fashion among physicists. . . . Most of the authors who started using this concept soon after the end of the war actually belonged to a younger generation who also favored different approaches to physical problems.

Kojevnikov points to Henry Small's analysis of citations in 16 major physics journals in the 1920s, showing that the annual rate of citations of Einstein's 1917 paper on the quantum theory of radiation was rising in the early 1920s; it was one of the most frequently cited papers in the decade, second only to Compton's paper of 1923.[71]

Going back a decade, we learn from McCormmach that "in Europe at this time [1907–1910], the interpretation of the quantum theory as one of light quanta was held only by a very small minority, while in Britain the situation was reverse and nearly everyone who had any point of view at all considered the theory to be based on an atomic constitution of radiation, or of energy in general" (he mentions Larmor, Schuster, and Jeans).[72]

From Roger Stuewer's comprehensive book on the Compton effect I infer that the *major* physicists were almost evenly divided. On the pro-corpuscular side were, in addition to Einstein, Louis de Broglie, William H. Bragg, James Jeans, Henri Poincaré, Erwin Schrödinger, and Johannes Stark; opponents included Niels Bohr,

71. Alexei Kojevnikov, "Einstein's fluctuation formula and the wave-particle duality," in Y. Balashov and V. Vizgin eds., *Einstein studies in Russia* (Boston, 2002), 181–228. Kojevnikov discusses papers by Ehrenfest, Wolfke and others. Henry Small, "Recapturing physics in the 1920s through citation analysis," *Czechoslovak journal of physics, B36* (1986), 142–147. Compton's paper received 78 citations, Einstein's 1917 paper received 76. It is not clear whether Small has counted the citations (at least 1) of the original 1916 publication of Einstein's paper, which was reprinted in a more widely-circulated journal in 1917; see ref. 6.

72. McCormmach (ref. 3), 375. Later he notes that in 1910 Planck, Lorentz, and Sommerfeld "all spoke out publicly against light quanta" (ref. 3, p. 382, no. 80).

H.A. Lorentz, O.W. Richardson, Arnold Sommerfeld, and J.J. Thomson.[73] But Thomson, included on that list as an opponent of Einstein's LQH, held views that were (or were often seen as) corpuscularian. Sommerfeld by 1922 was on the verge of accepting the LQH. Richardson was struggling to understand how radiation "behaves as though it possessed at the same time the opposite properties of extension and localisation." H.A. Kramers and J.C. Slater might be considered opponents on the basis of their co-authorship of the Bohr-Kramers-Slater paper (see next section), but both were more favorable before they came under Bohr's influence.[74]

While Lorentz in his public statements was critical of the LQH, he described its advantages as well as its disadvantages in a long letter of 1909 to Einstein. He concluded, [75]

> It is a real pity that the light quantum hypothesis encounters such serious difficulties, because otherwise the hypothesis is very pretty, and many of its applications that you and Stark have made of it are very enticing. But the doubts that have been raised carry so much weight with me that I want to confine myself to the statement: "If we have a ponderable body in a space enclosed by reflecting walls and filled with ether, then the distribution of the energy between the body and the ether proceeds *as if* each degree of freedom of the ether could take up or give off energy only in portions of the magnitude $h\nu$." As you see, not much is gained thereby, the "*as if*" would have to be elucidated through further analysis.

It is probably not fruitful to focus narrowly on the reception of the LQH while ignoring the other corpuscular theories of radiation discussed in the early 20th century.

73. Stuewer, *Compton effect* (ref. 4), 6–14, 28–29, 59, 68, 70, 222. L. de Broglie, *Recherches sur la théorie des quanta* (Paris, 1924); reprinted in *Annales de Physique, 3* (1925), 22–128. On his earlier acceptance of the "light molecules" see "Rayonnement noir et quanta de lumière," *Journal de physique et le radium, 3* (1922), 422–428; "A tentative theory of light quanta," *Philosophical magazine, 47* (1924), 446–458. Fifty years later he asserted that by 1919 he had accepted "the coexistence of waves and particles in radiation, propounded in 1905 by Einstein." See Louis de Broglie, "The beginnings of wave mechanics," in W.C. Price, S.S. Chissick, and T. Ravensdale eds., *Wave mechanics: The first fifty years*, (New York. 1973), 12–18, on 12. The idea that de Broglie was led to propose his wave theory of matter by reflecting on the Compton effect is unlikely in view of his earlier work. Unlike Compton, he was directly influenced by reading Einstein's papers. See his letter quoted by Sopka (ref. 4), 112.
74. On Thomson see McCormmach, ref. 3. Arnold Sommerfeld, *Atombau und Spektrallinien* (Braunschweig, 1919), 200; *Atomic structure and spectral lines* (New York, 1923, trans. from the 3rd German edn. of 1922), vi [Preface dated Jan 1922], 35–45. O.W. Richardson, *The electron theory of matter* (2nd edn, Cambridge, 1916), 507. On Kramers, see ref. 45. On Slater, see ref. 56.
75. H.A. Lorentz, letter to Einstein, 6 May 1909, see ref. 25, Doc. 153, quotation from *Collected papers of Albert Einstein,* English translation (Princeton, 1995), *5*, 112. See Einstein's reply, 23 May 1909, ibid., 122–126. Again, on 27 Jan 1911, Einstein tried to clarify his position: "I am not the orthodox light-quantizer for whom you take me" (ibid., 175).

Some of those theories were first proposed to explain x-rays, which were not definitely known to be adequately described by Maxwell's electromagnetic wave theory until the discovery of x-ray diffraction in 1912. Before that it was reasonable to suppose that x-rays are corpuscular in nature, on the basis of their known properties. But after 1912 it was more reasonable to suppose that if x-rays and light are essentially the same phenomenon, differing only by having different values of a numerical parameter (wavelength or frequency), then all the arguments for the corpuscular nature of x-rays would also imply a corpuscular nature for light. Otherwise, if x-ray diffraction (or another wave property) had not been discovered until after 1923, the Compton effect would not initially have been considered a proof that *visible* light is corpuscular.

The relevant question is: which scientists were supporters or opponents of the corpuscular nature of light (not necessarily limited to the Einstein LQH) before 1923? Opponents would generally insist on the absolute validity of the wave theory of light, while supporters would argue that the wave theory, while adequate to account for many aspects of light such as interference, diffraction, and polarization, failed to explain several newly-discovered properties of electromagnetic radiation, and therefore had to be modified in some way.

In Table 1, I have listed the supporters and opponents of the LQH, based primarily on their publications and the accounts of historians.[76] There is a third category: authors of textbooks on optics or general physics who do not mention the LQH at

76. In addition to those mentioned above, the following publications supported a corpuscular view of light (not necessarily Einstein's LQH): Robert William Wood, *Physical optics* (New York, 1911, rept. 1929); Norman Robert Campbell, *Modern electrical theory* (2nd edn., Cambridge, Eng., 1913); James Jeans, *The dynamical theory of gases* (2nd edn., Cambridge, Eng., 1916);W.H. Bragg and W.L. Bragg, *X-rays and crystal structure* (2nd edn., London, 1916); Daniel F. Comstock and Leonard T. Troland, *The nature of matter and electricity: An outline of modern views* (New York, 1917); A.S. Eddington, *Space, time and gravitation* (Cambridge, UK, 1920), 182; Fritz Reiche, *Die Quantentheorie: Ihr Ursprung und ihre Entwicklung* (Berlin, 1921); English trans., *The quantum theory*, trans. H.S. Hatfield and Henry L. Brose (London, 1922). Planck by 1920 was almost ready to accept the LQH; see *Das Wesen des Lichts* (Berlin, 1920) and his Nobel lecture (June 2, 1920), translated as "The genesis and present state of development of the quantum theory" *Nobel lectures* (ref. 35), 407–418.

Opponents (other than those already mentioned): Max Laue, letters to Einstein, 2 June 1906 and 27 Dec 1907, docs 37 and 70 in ref. 75; Planck, letter to Einstein, 6 Jul 1907, in ref. 75, doc. 47; Walther Nernst, letter to Arthur Schuster, 10 Mar 1910, quoted by Diana Barkan, *Walther Nernst and the transition to modern physical science* (Cambridge, UK, 1999), 183; O.W. Richardson and K.T. Compton (ref. 29); Siegfried Valentiner, *Die Grundlagen der Quantentheorie in elementare Darstellung* (Braunschweig, 1914), 14–16; G.W.C. Kaye, *X-rays* (London, 3rd edn., 1918), 236–246; Max Born, *Der Aufbau der Materie* (Berlin, 1922), 41; L. Brillouin, *La theorie des quanta et l'atome de Bohr* (Paris, 1922), 107–109; Franz Exner, *Vorlesungen über die Grundlagen der Naturwissenschaften* (Leipzig, 2nd edn. 1922), 426, 518.

Table 1. Supporters and Opponents of a Corpuscular Aspect of Electromagnetic Radiation Before 1923. (Numbers in parentheses indicate age in 1920, if known; * means may have died before 1920.)

Supporters	**Opponents**
William Henry Bragg (58)	Alfred Berthoud (46)
William Lawrence Bragg (30)	Niels Bohr (35)
Louis de Broglie (28)	Max Born (38)
Maurice de Broglie (45)	Leon Brillouin (31)
Norman Robert Campbell (40)	Arthur Holly Compton (28) CV
Daniel F. Comstock (87*)	Karl Taylor Compton (33)
James Arnold Crowther (37)	Peter Debye (36)
Arthur Stanley Eddington (38) B.S.	William Duane (48)
Paul Ehrenfest (40)	Franz Exner (71)
Albert Einstein (41)	G.W.C. Kaye (40) CV
C.D. Ellis	Max Laue (40)
Arthur Haas (36)	H.A. Lorentz (67)
Arthur Llewelyn Hughes (37)	Robert A. Millikan (52)
James Jeans (43)	J.W. Nicolson (39)
Abram Joffe (40)	Max Planck (62)
G.W.C. Kaye (40) CV	O.W. Richardson (41)
H.A. Kramers (26) B.S.	Arnold Sommerfeld (52)
Rudolf Ladenburg (38)	Siegfried Valentiner (44)
Oliver Lodge (69)	
D.V. Mallik (54)	
Walther Nernst (56)	
Fritz Reiche (37)	
Erwin Schrödinger (33) B.S.	
Johannes Stark (46)	
J.J. Thomson (64)	
Leonard T. Troland	
Mieczyslaw Wolfke	
Robert W. Wood (52)	

all but simply present the wave theory as the correct and only explanation of light. If one goes back to 1905 this category would be the largest, but in my systematic survey for 1916–1922, it is larger than the category of opponents but smaller than that of supporters. I have also noted those who first opposed it and then supported it *before* 1923 (CV for "convert"), and those who supported it before 1923 and then opposed it (B.S. for "backslider").

Perhaps the best example (other than Einstein) of a physicist who strongly supported the LQH before 1923 is Fritz Reiche (1883–1969), Professor of Physics at the University of Breslau. He was in the audience when Einstein spoke about his hypothesis at the meeting of the Gesellschaft Naturforscher und Ärtze in Salzburg (September 1909). Later he collaborated with Ladenburg on research that played an important role in the early development of matrix mechanics. His book on quantum theory was published in German in 1921 (preface dated October 1920) and an English translation appeared in 1922. He asserted that the LQH explains "simply and naturally a number of phenomena which completely baffled the undulatory theory," beginning (not, as one might expect, with the photoelectric effect) with phosphorescence, especially Stokes's Law. He notes the concept of a speckled or "beady" wave front proposed by J.J. Thomson, before 1905, to account for the ionization of gases by x-rays, a phenomenon analogous to phosphorescence. He then reviews Einstein's law of the photoelectric effect, verified by Millikan; fluorescence in the regions of both x-rays and visible radiation; and the reverse of the photoelectric effect in which the kinetic energy of electrons is transformed back into the energy of light. Other phenomena supporting the quantum hypothesis are the Franck-Hertz experiment; Stark's experiments showing that canal rays emit "kinetic radiation" only when their speeds exceed a certain value; and photochemical reactions. Einstein's deduction of Planck's law by combining the Bohr model of the atom with the LQH is noted.

Reiche showed explicitly what was vaguely alluded to in much of the literature I have examined: the evidence for the corpuscular nature of light, and for the LQH in particular, did not come from just one phenomenon like the photoelectric effect; it came from many experiments and theoretical calculations, all pointing in the same direction. Even if the corpuscular theory could not yet explain as many phenomena as the wave theory, it was moving ahead rapidly and would soon take the lead. In the terminology of the philosopher Imre Lakatos, it was a "progressive research programme," or as Gonzalo Munevar expressed it, it offered "promise more than performance." Millikan recognized this fact in his Faraday lecture of 1924: he asserted that although he could not accept the LQH even after the discovery of the Compton effect, "The times are, however, pregnant with new ideas, and atomic conceptions in the field of ether waves seem to hold at the moment the master-key to progress."[77]

77. Reiche (ref. 76). Cf. Benjamin Bederson's article, "Fritz Reiche and the Emergency Committee in Aid of Displaced Foreign Scholars," *Physics in perspective*, *7* (2005, pub. 2006), 453–472, which includes in addition to a biography of Reiche some information about the impact of this book. Lakatos presents his views in "Falsification and the methodology of scientific research programmes," in I. Lakatos and A. Musgrave eds., *Criticism and the growth of knowledge*, (New York, 1970), 91–196. Munevar's thesis about promise and performance comes from a private communication but is briefly discussed in his "Reflections on Hull's remarks" in E.B. Hook ed., *Prematurity in scientific discovery*, (Berkeley, 2002), 342–345. The Millikan quote is from his "Atomism in modern physics," *Journal of the Chemical Society, 125* (1924), 1405–1417, on 1417.

9. THE IMPACT OF COMPTON'S DISCOVERY

As is well known, Bohr and a few other leading physicists were persuaded to abandon their opposition to the Light Quantum Hypothesis by the Compton effect, after the experimental confirmation of Compton's predictions and the experimental refutation of the Bohr-Kramers-Slater theory. Here I want to go beyond the leaders to see how other physicists reacted to this new evidence, and whether they gave it more or less weight than the confirmation of Einstein's theory of the photoelectric effect.

One measure of the impact of Compton's paper is the number of citations it received. As noted above, according to Henry Small it was the most frequently cited paper in 16 major physics journals in the decade 1920–1929. There were 78 citations in 7 years, but this number underestimates its impact; by 1926 it was not even necessary to give a citation to Compton's original paper when discussing his effect. Yet the texts of these papers tell us little or nothing about the relative importance of the photoelectric effect and the Compton effect in persuading the author to accept the LQH.[78]

Two of the earliest books to educate physicists about the Compton effect were Millikan's second edition of *The electron* and Sommerfeld's fourth edition of *Atombau und Spektrallinien*, both published in 1924. Millikan called it "the best evidence yet found in favor of Einstein's hypothesis of localized light quanta"—a hypothesis that "is having new and remarkable successes" despite the difficulty of reconciling it with the wave properties of light. Sommerfeld wrote that the Compton effect was the most important discovery that could have been made in the present state of physics, one that had changed his own views in the direction of the extreme LQH. The great prestige of these physicists and their previous skepticism about the reality of light quanta must have made a deep impression on many readers.[79]

Karl K. Darrow called attention to Compton's work in a article of 1925 which was part of his series on "contemporary advances in physics" published in the *Bell technical journal*. Darrow's articles seem to have reached a fairly large audience,

78. Small (ref. 81); G. Hoffmann, "Über den Comptoneffekt bei γ-Strahlen," *Zeitschrift für Physik, 36* (1926), 251–258; G.E.M. Jauncey, "Note on the quantum theory of the unmodified line in the Compton effect," *Physical review, 27* (1926), 687f. While the *Science citation index* can be an extremely useful tool for studying the reception of new theories and discoveries if one actually looks at the citing articles, one cannot assume without further research that there is a strong correlation between the number of citations of an article and its importance. On this point see S.G. Brush, "The most-cited physical sciences publications in the 1945–1954 *Science citation index*," *Current contents,* no. 20 (14 May, 1990), 7–17; no. 42 (15 Oct 1990), 8–13; no. 43 (22 Oct 1990), 7–16.

79. Millikan, *The electron: Its isolation and measurement and the determination of some of its properties* (2nd edn., Chicago, 1924); 256. Arnold Sommerfeld, *Atombau und Spektrallinien* (4. Aufl., Braunschweig, 1924), viii. Stuewer (ref. 4) and Brown (ref. 4) discuss the responses in the physics research literature so I will focus instead on reviews and books.

especially after they were collected in a 1926 book *Introduction to contemporary physics*. (His exposition of quantum mechanics was even translated into German, a striking example of "bringing coals to Newcastle."). Compton himself recommended Darrow's article (1925), in his paper with Simon in *The physical review*. Around the same time Walther Gerlach published a graduate text in German, followed by an English translation; he asserted: "the Compton effect more than all other quantum phenomena necessitates the assumption of light quanta and their directed emission."[80]

Compton was able to publicize his discovery in a short article in *Scientific American* where he made a point of mentioning Einstein's name in connection with the LQH. The layout of the article featured photos of Einstein and Michelson as advocates of the opposing particle and wave theories, but no picture of Compton (perhaps the Matthew effect was already at work).[81]

I did not find any discussion of the Compton effect in undergraduate textbooks published before 1928. In that year two books recognized it as important evidence for the LQH, more or less comparable to the photoelectric effect.[82] Two others mentioned the Compton effect but seemed to consider it somewhat weaker evidence.[83] Compton did not seem to profit from patriotism: none of the four authors was American. In 1929 two more authors featured the Compton effect as being perhaps the best evidence for the particle nature of light: one was an American physicist writing on the history of physics, the other a German physicist giving guest lectures at Ohio State University.[84] A Dutch Jesuit was one of the first to state explicitly that the Compton effect "shows even more clearly [than the photoelectric effect] that light has an atomic structure" in a German book published in 1929 and translated into English in 1930.[85]

80. Karl K. Darrow, "Some contemporary advances in physics—VII. Waves and quanta," *Bell technical journal, 4* (1925), 280–326.; *Introduction to contemporary physics* (New York, 1926); *Elementare Einführung in die Wellenmechanik*, translated from English and "ergänzt" by E. Rabinowitch, and foreword by E. Schrödinger (Leipzig, 1929). A.H. Compton and A.W. Simon (ref. 63), 289. Walther Gerlach, *Matter, electricity, energy: The principles of modern atomistics and experimental results of atomic investigation*, translated from the 2nd German edn. of 1926 (New York, 1928), 262.
81. A.H. Compton (ref. 52).
82. Wilhelm H. Westphal, *Physik: Ein Lehrbuch für Studierende an den Universitäten und technischen Hochschulen* (Berlin 1928). Harold Albert Wilson, *Modern physics* (London, 1928).
83. Karl Försterling, *Lehrbuch der Optik* (Leipzig, 1928). Arthur Haas, *The world of atoms, Ten non-mathematical lectures*, trans. and rev. H.S. Uhler (New York, 1928).
84. Florian Cajori, *A history of physics* (rev. edn., New York, 1929). Alfred Landé, *Vorlesungen über Wellenmechanik, gehalten an der Staatsuniversität zu Columbus U.S.A.* (Leipzig, 1930).
85. Theodor Wulf, S. J., *Modern physics: A general survey of its principles*, translated from the 2nd German edn. of 1929 (London, 1930).

I have attempted to examine all the books and review articles by physicists in English, German, or French, in the 30 years following Einstein's publication of his Light Quantum Hypothesis, to see whether the authors accepted or rejected it, and what reasons they gave. A few publications by chemists and astronomers were included. Publications by Einstein and A.H. Compton are not included, since they were promoters rather than receivers of the theory. This is a preliminary report, based on more than 250 books and articles that appeared in the two decades beginning with Millikan's confirmation of Einstein's photoelectric equation: 1916–1935.[86] They have been divided into two major categories: (1) monographs and review articles, directed to an audience of physicists; (2) textbooks and popular articles, directed to students and the public. The viewpoint of each publication was assigned to one of the following: "strongly supports LQH (or other corpuscular theory)" "leans toward LQH" "neutral" "leans against LQH" (or doesn't mention it but supports the wave theory of light) and "strongly rejects LQH." The distinction between LQH and other corpuscular theories, which is significant before 1921 (see previous section), is mostly ignored by writers in this later period; I noted only a handful who rejected the LQH but supported another corpuscular theory.

Besides the photoelectric effect and the Compton effect, there were several other possible reasons to accept the LQH:

(1) According to Einstein and Poincaré, its validity is a logical consequence of the law of blackbody radiation, subject to certain assumptions.[87]
(2) The success of Bohr's model of the hydrogen atom (1913) depends in part on the assumption that energy is absorbed and emitted in quanta (although one could still argue that the quantization applied only to the interaction of radiation and matter, not to radiation in free space).

86. The total number that might belong to this category is at least twice as large. My current sample is not random but includes the items more easily available in American libraries at the beginning of the 21st century. As explained in more detail in my earlier publications (see ref. 2), I consider textbooks one of the most useful sources of information about new scientific ideas, even though they may reflect the views adopted by leaders in the field several years earlier (obtaining quantitative estimates of this time lag is one of the goals of my research). Research articles in scientific journals often do not explain why a new idea is adopted; they either use it or they don't. The *Physics citation index 1920–1929* (see headnote) was useful in locating citations of Compton's 1923 paper in major journals published within the first two or three years, but after that it was simply referred to as "the Compton effect" with no citation.
87. *The collected papers of Albert Einstein* (ref. 5), *2* 134–169, 541–553; Klein, "Einstein's first paper" (ref. 67); Poincaré, "Sur la théorie des quanta," *Journal de physique théorique et appliquée [series 5], 2* (1912); McCormmach, "Poincaré" (ref. 3).

(3) The Raman effect, discovered a couple of years after the Compton effect but predicted earlier by Smekal, also indicates that light is quantized.[88]
(4) As noted above, the success of relativity theory implies that light is composed of particles having mass as well as energy, and undermines the credibility of any wave theory that requires the existence of an ether.
(5) The confirmation, by Lebedew and by Nichols and Hull, of Maxwell's prediction that electromagnetic radiation exerts a mechanical pressure on a surface, might suggest that light has corpuscular properties even though the prediction was based on a wave theory.[89]
(6) The ionization of a gas by x-rays, which implied (according to J.J. Thomson) that the energy of the rays is concentrated in certain regions on the wave front rather than being spread out uniformly.
(7) One of the most convincing arguments *against* the Newtonian corpuscular theory—that the speed of light is greater in a less dense medium—does not apply to the LQH.[90]
(8) According to the quantum mechanics of Heisenberg, Schrödinger, and Dirac, an entity can behave like a wave motion in some experiments and like a stream of particles in another; particles and waves can both be described by the same equations. So the existence of wave properties like interference is not inconsistent with the LQH.

In my current sample the number of authors naming any of these as the *primary* reason for adopting the LQH is too small to be significant, but further research may change that conclusion.

My survey shows (Table 2) that for 1916–20, monographs (including technical reviews) were about evenly split between supporters of a particulate character of light (along with its wave properties) and those who rejected it (or did not mention it while endorsing the wave theory of light). A slim majority (about 57 percent) of the monographs published in the period 1921–25 favored the LQH or a similar corpuscular theory, and this is true even though only 5 percent mentioned the Compton effect as evidence for it; most gave the photoelectric effect as the only evidence.

The majority in favor of the LQH grew to about 84 percent in 1926–30; about 58 percent of all authors specified the Compton effect as being either stronger

88. Chandrasekhara V. Raman, "A new radiation," *Indian journal of physics, 2* (1928), 387–398, confirming a prediction by Adolf Smekal, "Zur Quantentheorie der Dispersion," *Naturwissenschaften, 11* (1923), 873–875. See Rajinder Singh, "C.V. Raman and the discovery of the Raman effect," *Physics in perspective, 4* (2002), 399–420.
89. H.A. Lorentz, "Radiation" (ref. 39).
90. Jacob Frenkel, *Einführung in die Wellenmechanik* (Berlin, 1929), 12. Arnold Sommerfeld asserted that this argument did not even apply to the Newtonian theory—it was based on a confusion between phase and group velocities. See also his *Wave mechanics* (New York, 1930), 208.

evidence than the photoelectric effect, or at least as strong (C + C > P + C = P). 35 percent mentioned the photoelectric effect (P + P > C + P = C).

In the final half-decade, 1931–35, the balance shifted even more strongly toward the LQH, favored by about 92 percent. Now a slightly higher proportion (62 percent) of all authors supported the Compton effect, while 54 percent mentioned the photoelectric effect.

Among textbooks and popular articles published in 1916–1920, only one (by Comstock and Troland) out of 18 favored the Light Quantum Hypothesis. In 1921–25 it was supported by almost one-third (31 percent). This increased to about 70 percent in 1926–30, and to 84 percent in 1931–35. But now we see the beginning of a split between the monographs and the textbooks regarding the reason for adopting the hypothesis. In the half-decade 1926–30, only 28 percent of textbook authors mentioned the Compton effect as evidence (stronger than or as strong as the photoelectric effect) for the LQH, compared with 62 percent of monograph authors. In the same period 52 percent of textbook authors mentioned the photoelectric effect compared with 35 percent of monograph authors.

In the half-decade 1931–35, 84 percent of textbook authors favored the LQH. But only 49 percent mentioned the Compton effect, while 55 percent cited the photoelectric effect as a reason for supporting the LQH. This was about the same proportion as among the monograph authors (54 percent). While the gap between monographs and textbooks might seem to be narrowing with time, it should be noted that I found only a few (13) monographs published in 1931-35, compared with the much larger number of textbooks (55), so the data for monographs may not be representative.

My provisional conclusion (subject to further research) is that starting around 1926, when the Compton effect was probably fairly well known to most physicists active in research or teaching, authors of books and reviews directed to physicists were more likely to call it the most important evidence for the LQH than were the authors of textbooks and popular articles, who tended to cite the photoelectric effect more often.

Why the difference? My guess is that the Compton effect was considered more elegant physics. It is a direct application of the beloved conservation laws for energy and momentum, and it involves no adjustable parameters. From a minimum of assumptions it gives you maximum results (a simple formula for the change of wavelength of the x-ray, and relations between the scattered x-ray and the recoil electron). It combines the best features of classical physics with the one formula of quantum theory that is familiar (though not necessarily comprehensible) to all physicists, $E = h\nu$ along with its relativistic corollary, p [momentum] = $h\nu/c$. Moreover, it survived a dramatic challenge from one of the most authoritative physicists in the world (Bohr).

The photoelectric effect, on the other hand, gives you only one result, the maximum energy of the ejected electron, at the cost of introducing a variable parameter (the energy needed to bring the electron to the surface of the metal), and it took lots of tedious work to nail down that result.

But it's much easier to explain the photoelectric effect to students! You don't have to do any algebra or trigonometry. Moreover, it has an interesting practical application that should be familiar to almost all students: the "electric eye" that automatically opens a door when you approach it, or prevents an elevator door from hitting you.[91]

It is not obvious that physicists would have accepted the LQH on the basis of either the photoelectric effect or the Compton effect alone, or that acceptance would have come earlier if the chronological order of the discovery of the two effects (and their theoretical explanation) had been reversed. One exception to the wave properties of light, no matter how elegant or well-documented, probably would not have been enough. The photoelectric effect, along with corpuscular theories based on x-ray research, created doubts about the absolute validity of the wave theory of light but not enough to overthrow it. It took at least two discoveries, both of which could be explained by the same hypothesis, to tip the balance.

There is one other reason why the Compton effect might have carried more weight, pointed out by Compton himself: it involved a confirmed novel prediction. Compton's assertion that the photoelectric effect did *not* have this virtue was somewhat misleading; Einstein predicted a linear relation between maximum kinetic energy and frequency at a time when such a relation had not been established. But Compton also predicted a *qualitatively new* phenomenon: the recoil electron, and one could argue that this should count more than a quantitative prediction about a qualitatively known phenomenon.

The acceptance of the LQH based, in large part, on the Compton effect, seems highly relevant to an ongoing debate among philosophers of science.[92] One group, following Karl Popper and Imre Lakatos, advocates "predictivism": a novel prediction is better evidence for a hypothesis than a similar "postdiction" or deduction of known facts. Another group argues that the evidential value of a fact cannot logically depend on when we knew it; any apparent advantage of a novel prediction is purely psychological (a "surprise" effect).

91. Similarly, Morgan's chromosome theory of heredity was accepted for different reasons by experts on genetics (who liked the elegant but rather complicated "nondisjunction" and by other biologists (who stressed its ability to make a map of the chromosome and to explain Mendelian genetics); see Brush, "How theories" (ref. 2).

92. Brush, "Dynamics of theory change: The role of predictions" (ref. 2). On "predictivism" see Peter Lipton, "Prediction and prejudice," *International studies in the philosophy of science, 4:1* (1990), 51–65; Lipton, *Inference to the best explanation* (London, 1991); Patrick Maher, "Prediction, accommodation, and the logic of discovery," in *PSA 1988* (East Lansing, MI, 1988), *1*, 273–285. In a recent exchange of letters, Lipton admitted that he is "focused on the normative question": whether scientists *should* give more weight to novel predictions, not whether they actually do so. Lipton, "Accommodation or prediction?" *Science, 308* (2005), 1411–1412. My own view is not anti-predictivist but pluralist: sometimes scientists use the hypothetico-deductive method, sometimes they use other approaches.

Table 2. Acceptance of Particle Nature of Radiation*

	Favorable			Unfavorable		Total
Monographs, technical reviews	++	+	0	–	--	N
1916	2	1	0	0	0	3
1917	0	0	0	1	0	1
1918	1	0	0	0	1	2
1919	0	0	2	0	1	3
1920	0	1	2	1	1	5
Subtotal for 1916–20	3	2	4	2	3	14
1921	2	4	2	3	0	11
1922	2	1	1	4	1	9
1923	0	4	0	1	0	5
1924	2	3	0	2	1	8
1925	1	2	0	1	0	4
Subtotal for 1921–25	7	14	3	11	2	37
1926	3	2	0	1	0	6
1927	1	3	2	1	1	8
1928	1	6	0	0	0	7
1929	0	5	0	0	0	5
1930	2	3	0	0	0	5
**Subtotal for 1926–30	7	19	2	2	1	31
1931	0	1	0	0	0	1
1932	0	4	0	1	0	5
1933	0	4	0	0	0	4
1934	0	1	0	0	0	1
1935	0	2	0	0	0	2
Subtotal for 1931–35	0	12	0	1	0	13
Textbooks, popular articles	++	+	0	–	--	N
1916	0	0	0	4	0	4
1917	0	1	2	2	0	5
1918	0	0	0	1	1	2
1919	0	0	1	3	0	4
1920	0	0	1	2	0	3
Subtotal for 1916–20	0	1	4	12	1	18

*Symbols: ++ = strongly supports LQH; + = leans toward LQH; 0 = neutral; – = leans against LQH (or doesn't mention it but supports wave theory of light); -- = strongly rejects LQH

Table 2. (Continued)

	Favorable			Unfavorable		Total
1921	2	0	0	3	0	5
1922	0	0	0	0	1	1
1923	2	0	0	3	0	5
1924	0	3	0	5	3	11
1925	1	0	1	1	1	4
Subtotal for 1921–25	5	3	1	12	5	26
1926	3	7	0	1	0	11
1927	1	7	0	3	0	11
1928	1	4	3	5	0	13
1929	4	5	0	4	0	13
1930	3	10	0	3	0	16
**Subtotal for 1926–30	13	33	3	16	0	64
1931	1	4	0	1	0	6
1932	5	3	1	2	0	11
1933	1	8	0	1	0	10
1934	3	9	0	1	0	13
1935	2	10	1	2	0	15
Subtotal for 1931–35	12	34	2	7	0	55

If Compton and the predictivist philosophers are correct, there should be some evidence of that in the literature I examined. But only a few authors even mentioned the fact that Compton had predicted recoil electrons, and none of them stated that his theory was more likely to be valid *because* he predicted them *before* they were discovered.[93]

93. The closest I have found to this statement is in Edward N. DaC. Andrade, *The structure of the atom* (3rd edn., New York, 1926), 694. See also Floyd K. Richtmyer, *Introduction to modern physics* (2nd edn., New York, 1934), 599; Herbert S. Allen, *Electrons and waves: An introduction to atomic physics* (London, 1932), 135. Allen, however, uses the word "predict" for both the lengthening of the scattered ray (which was known) and the existence and motion of the recoil electron (which was not). As noted in my earlier papers, 20th century physicists generally follow that usage; when they want to emphasize that the predicted phenomenon was *not* known they may say "predict in advance." Hughes and DuBridge (ref. 65) stated: "As there was little or no experimental evidence for or against the equation in 1905, this equation is to be regarded as one of the great and successful predictions in physics, comparable with that of Maxwell as to the electromagnetic character of light" (p. 8). Note that the credit for a confirmed novel prediction is given here to the photoelectric equation, not to the LQH from which it was derived.

Table 3. Evidence for Particle Nature of Radiation**

	P	**P > C**	**C = P**	**0**	**C > P**	**C**	**N**
Monographs, technical reviews							
1916	3	0	0	0	0	0	3
1917	0	0	0	1	0	0	1
1918	1	0	0	1	0	0	2
1919	0	0	0	3	0	0	3
1920	1	0	0	4	0	0	5
Subtotal for 1916–20	5	0	0	9	0	0	14
1921	4	0	0	7	0	0	11
1922	3	0	0	6	0	0	9
1923	2	0	0	3	0	0	5
1924	3	0	0	3	2	0	8
1925	3	0	0	1	0	0	4
Subtotal for 1921–25	15	0	0	20	2	0	37
1926	0	1	1	1	1	2	6
1927	0	0	1	7	0	0	8
1928	1	2	1	0	0	3	7
1929	0	0	2	0	1	2	5
1930	0	1	1	0	0	3	5
Subtotal for 1926–30	1	4	6	8	3	9	31
1931	0	0	1	0	0	0	1
1932	0	1	1	2	1	0	5
1933	1	1	2	0	0	0	4
1934	0	0	0	0	1	0	1
1935	0	0	0	0	2	0	2
Subtotal for 1931–35	1	2	4	2	4	0	13
Textbooks, popular articles							
1921	2	0	0	3	0	0	5
1922	0	0	0	1	0	0	1
1923	2	0	0	3	0	0	5
1924	2	0	0	9	0	0	11
1925	0	0	0	4	0	0	4
Subtotal for 1921–25	6	0	0	20	0	0	26

**Symbols: P = only photoelectric effect is mentioned; P > C = photoelectric is stronger evidence than Compton effect; C = P, the two are equally strong; 0 = neither effect mentioned or particle nature of light rejected; C > P = Compton effect is stronger evidence than photoelectric; C = only Compton effect is mentioned.

Table 3. (Continued)

	P	P > C	C = P	0	C > P	C	N
Textbooks, popular articles							
1926	3	2	1	3	1	1	11
1927	7	0	0	4	0	0	11
1928	1	2	2	8	0	0	13
1929	2	0	3	3	4	1	13
1930	4	4	2	3	1	2	16
Subtotal for 1926–30	17	8	8	21	6	4	64
1931	2	0	0	2	2	0	6
1932	0	2	2	3	1	3	11
1933	3	0	3	1	1	2	10
1934	4	0	4	1	3	1	13
1935	4	3	3	2	2	0	15
Subtotal for 1931–35	13	5	12	12	9	6	55

If prediction were really an important factor in the *acceptance* of theories one would expect the Raman effect to get more credit than it does, since Raman was confirming an earlier prediction by Smekal.

Popperians may find some consolation in the fact that while physicists did not give Compton extra credit for the novelty of his prediction, some of them did praise the Bohr-Kramers-Slater theory for being so precise in its predictions as to be immediately and clearly falsified.[94]

A valid theory should make testable predictions whenever possible, but that does not mean it must make confirmed novel predictions *before* it is accepted as valid. Quantum mechanics is a famous counter example: a theory that was widely accepted before its novel predictions were tested.[95] If one must have an explicit criterion for acceptance (a requirement I find rather dubious) here's a better one from the 1920s discussion of the nature of light: "A theory must pass a very strict test nowadays; it must not only be accurate, it must be a convenient and powerful instrument of thought."[96] As Einstein himself stated, the Light Quantum Hypothesis was not intended to end the debate about the nature of light but to open a new and

94. Charles D. Ellis, "The light-quantum theory," *Nature, 117* (1926), 895–897, on 896. See also Pauli, letter to Kramers, 27 Jul 1925 (ref. 58).
95. Brush, "Dynamics of theory change: The role of predictions" (ref. 4); Robert Marc Friedman, *The politics of excellence: Behind the Nobel Prize in science* (New York, 2001), 170–176.
96. T.L. Eckersley, "The Compton scattering and the structure of radiation," *Philosophical magazine, 2* (1926), 267f, on 286.

more fruitful period of research. Compton's own theory of his effect was certainly not the final answer either, but it provoked others like Schrödinger, Dirac, Klein, and Nishina to work out a more accurate and comprehensive quantum-mechanical theory.[97] It was not until the 1960s that our present understanding of quantum optics began to emerge, with the work of Roy Glauber, John Hall, and Theodor Hänsch, recently recognized by the award of the 2005 Nobel Prize in physics.[98]

10. CONCLUSIONS

The establishment of the particle nature of light—without denying its wave nature—was a revolutionary event in physics, as Einstein suspected in 1905. It was not accomplished by any single discovery such as the photoelectric effect or the Compton effect. It was not (as some physicists initially thought) a reversion to the Newtonian corpuscular theory, since that theory, like the wave theory of light, presupposed a mechanistic view of nature. Instead, it was the result of an accumulation of the theoretical and experimental efforts of many physicists, trying to explore and understand what might be called "anomalies" in the behavior of electromagnetic radiation. Einstein was the driving force in this effort, expending enormous energy in "hatching this favorite egg of mine," yet he was never quite successful in finding a solution that satisfied his own criteria. Bohr, who resisted the light quantum hypothesis to the bitter end (even though the success of his atomic model of 1913 was one of the factors that helped persuade other physicists to accept that hypothesis), was perhaps the first to realize that the mechanistic view would have to be abandoned in order to accept the quantum view of nature. In this paradigm switch, one had to give up not a particular theory such as the wave theory of light, but the *criteria for judging theories*, such as the requirement for a visualizable mechanistic explanation. Only then could the wave and particle theories peacefully coexist.[99]

As we know from 20th-century political history, fanatical proponents of one extreme doctrine may, when they finally abandon it, become equally fanatical proponents of the extreme opposite view. A remarkable example from the history of

97. See Brown, "Compton effect" (ref. 4).

98. Barbara Goss Levi, "Glauber, Hall, and Hänsch share the 2005 Nobel prize in physics," *Physics today*, *58:12* (Dec 2005), 19–22. For a recent critical evaluation of the light quantum concept see George Greenstein and Arthur G. Zajonc, *The quantum challenge: modern research on the foundations of quantum mechanics* (Sudbury, MA, 2005), chapt. 2 (I thank Gonzalo Munevar for this reference).

99. Einstein (ref. 25). The "egg" metaphor comes from his letter to Jakob Laub, 31 Dec 1909, in *Collected papers* (ref. 75), *5*, doc. 196. On Bohr see ref. 61. As Kojevnikov has noted, it is difficult to avoid describing this as a Kuhnian revolution since the participants themselves used Kuhnian terminology and seemed to be acting out Kuhn's scenario. Perhaps this is because Kuhn as a graduate student "witnessed directly the final resolution of the crisis" by quantum electrodynamics (ref. 71, p. 181)

physical optics is Robert Alexander Houstoun, lecturer in natural philosophy at the University of Glasgow and author of several commercially successful textbooks. He resisted the LQH into the 1930s, then apparently decided that his beloved wave theory was completely wrong and resurfaced in the 1960s as a fervent advocate of—*not* the Light Quantum Hypothesis—but of Newton's original corpuscular theory![100]

Of course one cannot convert the physics community by simply proclaiming that a new paradigm must be accepted. One needs empirical evidence. I suggest three major facts, to which each physicist might give a different weight, but all of which were needed to explain the conversion of (almost) the entire community: (1) the Compton effect; (2) the photoelectric effect; (3) all the other phenomena, especially those involving x-rays, specific heats of solids at low temperatures, and atomic spectra, which could not plausibly be explained by a wave theory but could (more or less accurately) be explained by some kind of quantum theory. The establishment of the Light Quantum Hypothesis was a major step toward the victory of the quantum worldview, but it was not the first or the last.

100. Robert A. Houstoun, *A treatise on light* (6th edn., London, 1930), 451–452; "Nature of light," *Journal of the Optical Society of America, 55* (1965), 1186–1188.

STEPHEN G. BRUSH

How ideas became knowledge: The light-quantum hypothesis 1905–1935

ABSTRACT

In 1905, Albert Einstein proposed as a "heuristic viewpoint" that light and other forms of electromagnetic radiation behave in some respects like streams of particles, each carrying energy $h\nu$ (h = Planck's constant, ν = frequency), even though they also behave like waves. This became known as the Light Quantum Hypothesis. J. J. Thomson and other physicists proposed similar but less quantitative ideas. When and why did physicists accept the LQH? It is shown that a significant number of physicists already accepted particulate aspects of radiation before the discovery of the Compton effect in 1923, and that research on the photoelectric effect played an important role in this acceptance. Compton argued that his research was stronger evidence for the LQH because it yielded a prediction about a previously unknown phenomenon, the recoil electron. But there is little evidence that other scientists gave extra credit for predicting a result before rather than after it was known. Probably the combination of both effects (and other evidence) was needed to persuade skeptics.

KEY WORDS: Albert Einstein, Robert A. Millikan, Arthur H. Compton, quantum theory, light, electromagnetic radiation, photoelectric effect, Compton effect.