Einstein's Revolutionary Light-Quantum Hypothesis[1]

Roger H. Stuewer[2]

Abstract

I sketch Albert Einstein's revolutionary conception of light quanta in 1905 and his introduction of the wave-particle duality into physics in 1909 and then offer reasons why physicists generally had rejected his light-quantum hypothesis by around 1913. These physicists included Robert A. Millikan, who confirmed Einstein's equation of the photoelectric effect in 1915 but rejected Einstein's interpretation of it. Only after Arthur H. Compton, as a result of six years of experimental and theoretical work, discovered the Compton effect in 1922, which Peter Debye also discovered independently and virtually simultaneously, did physicists generally accept light quanta. That acceptance, however, was delayed when George L. Clark and William Duane failed to confirm Compton's experimental results until the end of 1924, and by the publication of the Bohr-Kramers-Slater theory in 1924, which proposed that energy and momentum were conserved only statistically in the interaction between a light quantum and an electron, a theory that was not disproved experimentally until 1925, first by Walter Bothe and Hans Geiger and then by Compton and Alfred W. Simon.

Light Quanta

Albert Einstein signed his paper, "Concerning a Heuristic Point of View about the Creation and Transformation of Light,"[3] in Bern, Switzerland, on March 17, 1905, three days after his twenty-sixth birthday. It was the only one of Einstein's great papers of 1905 that he himself

---

[1] Paper presented at the HQ-1 Conference on the History of Quantum Physics at the Max Planck Institute for the History of Science, Berlin, Germany, July 5, 2007.
[2] Program in History of Science, Technology, and Medicine, Tate Laboratory of Physics, University of Minnesota, 116 Church Street SE, Minneapolis, MN 55455 USA; e-mail: rstuewer@physics.umn.edu.
[33] Einstein (1905).

Fig. 1. Albert Einstein (1879-1955) in the Patent Office in Bern, Switzerland. *Source*: Hoffmann (1972), p. 50.

called "very revolutionary."[4] As we shall see, Einstein (figure 1) was correct: His light-quantum hypothesis was not generally accepted by physicists for another two decades.

Einstein gave two arguments for light quanta, a negative and a positive one. His negative argument was the failure of the classical equipartition theorem, what Paul Ehrenfest later called the "ultraviolet catastrope."[5] His positive argument proceeded in two stages. First, Einstein calculated the change in entropy when a volume V_0 filled with blackbody radiation of total energy U in the Wien's law (high-frequency) region of the spectrum was reduced to a subvolume V. Second, Einstein used Boltzmann's statistical version of the entropy to calculate the probability of finding n independent, distinguishable gas molecules moving in a volume V_0 at a given instant of time in a subvolume V. He found that these two results were formally identical, providing that

$$U = n(R\beta/N)v,$$

where R is the ideal gas constant, β is the constant in the exponent in Wien's law, N is Avogadro's number, and v is the frequency of the radiation. Einstein concluded: "Monochromatic radiation of low density (within the range of validity of Wien's radiation formula) behaves thermodynamically as if it consisted of mutually independent energy quanta of magnitude $R\beta v/N$."[6]

Einstein cited three experimental supports for his light-quantum hypothesis, the most famous one being the photoelectric effect, which was discovered by Heinrich Hertz at the end of 1886[7] and explored in detail experimentally by Philipp Lenard in 1902.[8] Einstein wrote down his famous equation of the photoelectric effect,

---

[4] Einstein to Conrad Habicht, May 18 or 25, 1905. In Klein, Kox, and Schulmann (1993), p. 31; Beck (1995), p. 20.
[5] Quoted in Klein (1970), pp. 249-250.
[6] Einstein (1905), p. 143. In Stachel (1989), p. 161; Beck (1989), p. 97.
[7] For discussions, see Stuewer (1971); Buchwald (1994), pp. 243-244.
[8] Lenard (1902).

$$\Pi e = (R/N)\beta\nu - P,$$

where Π is the potential required to stop electrons (charge e) from being emitted from a photosensitive surface after their energy had been reduced by its work function P. It would take a decade to confirm this equation experimentally. Einstein also noted, however, that if the incident light quantum did not transfer all of its energy to the electron, then the above equation would become an inequality:

$$\Pi e < (R/N)\beta\nu - P.$$

It would take almost two decades to confirm this equation experimentally.

We see, in sum, that Einstein's arguments for light quanta were based upon Boltzmann's statistical interpretation of the entropy. He did *not* propose his light-quantum hypothesis "to explain the photoelectric effect," as physicists today are fond of saying. As noted above, the photoelectric effect was only one of three experimental supports that Einstein cited for his light-quantum hypothesis, so to call his paper his "photoelectric-effect paper" is completely false historically and utterly trivializes his achievement.

In January 1909 Einstein went further by analyzing the energy and momentum fluctuations in black-body radiation.[9] He now assumed the validity of Planck's law and showed that the expressions for the mean-square energy and momentum fluctuations split naturally into a sum of two terms, a wave term that dominated in the Rayleigh-Jeans (low-frequency) region of the spectrum and a particle term that dominated in the Wien's law (high-frequency) region. This constituted Einstein's introduction of the wave-particle duality into physics.[10]

Einstein presented these ideas again that September in a talk he gave at a meeting of the Gesellschaft Deutscher Naturforscher und Ärzte in Salzburg, Austria.[11] During the discussion, Max Planck took the acceptance of Einstein's light quanta to imply the rejection of Maxwell's electromagnetic waves which, he said, "seems to me to be a step which in my opinion is not yet necessary."[12] Johannes Stark was the only physicist at the meeting who supported Einstein's light-quantum hypothesis.[13]

In general, by around 1913 most physicists rejected Einstein's light-quantum hypothesis, and they had good reasons for doing so. First, they believed that Maxwell's

---

[9] Einstein (1909a).
[10] Klein (1964). For the wave-particle duality placed in a new context, see Duncan and Janssen (2007).
[11] Einstein (1909b).
[12] Planck, "Discussion." In Einstein (1909b), p. 825; Stachel (1989), p. 585; Beck (1989), p. 395.
[13] Stark, "Discussion." In Einstein (1909b), p. 826; Stachel (1989), p. 586; Beck (1989), p. 397.

electromagnetic theory had to be universally valid to account for interference and diffraction phenomena. Second, Einstein's statistical arguments for light quanta were unfamiliar to most physicists and were difficult to grasp. Third, between 1910 and 1913 three prominent physicists, J.J. Thomson, Arnold Sommerfeld, and O.W. Richardson, showed that Einstein's equation of the photoelectric effect could be derived on classical, non-Einsteinian grounds, thereby obviating the need to accept Einstein's light-quantum hypothesis as an interpretation of it.[14] Fourth, In 1912 Max Laue, Walter Friedrich, and Paul Knipping showed that X rays can be diffracted by a crystal,[15] which all physicists took to be clear proof that they were electromagnetic waves of short wavelength. Finally, in 1913 Niels Bohr insisted that when an electron underwent a transition in a hydrogen atom, an electromagnetic wave, not a light quantum, was emitted--a point to which I shall return later.

Millikan's Photoelectric-Effect Experiments

Robert Andrews Millikan began working intermittently on the photoelectric effect in 1905 but not in earnest until October 1912, which, he said, then "occupied practically all of my individual research time for the next three years."[16] Earlier that spring he had attended Planck's lectures in Berlin, who he recalled, "very definitely rejected the notion that light travels through space in the form of bunches of localized energy." Millikan therefore "scarcely expected" that his experiments would yield a "positive" result, but "the question was very vital and an answer of some sort had to be found."

Millikan recalled that by "great good fortune" he eventually found "the key to the whole problem," namely, that radiation over a wide range of frequencies ejected photoelectrons from the highly electropositive alkali metals, lithium, sodium, and potassium. He then modified and improved his experimental apparatus until it became "a machine shop in vacuo." He reported his results at a meeting of the American Physical Society in Washington, D.C., in April 1915; they were published in *The Physical Review* in March 1916 .[17] His data points fell on a perfectly straight line of slope h/e (figure 2), leaving no doubt whatsoever about the validity of Einstein's equation of the photoelectric effect.

---

[14] Stuewer (1975), pp. 48-68.
[15] Friedrich, Knipping, and Laue (1912); Laue (1912). In Laue (1961), pp. 183-207, 208-218.
[16] Millikan (1950), p. 100.
[17] Millikan (1916).

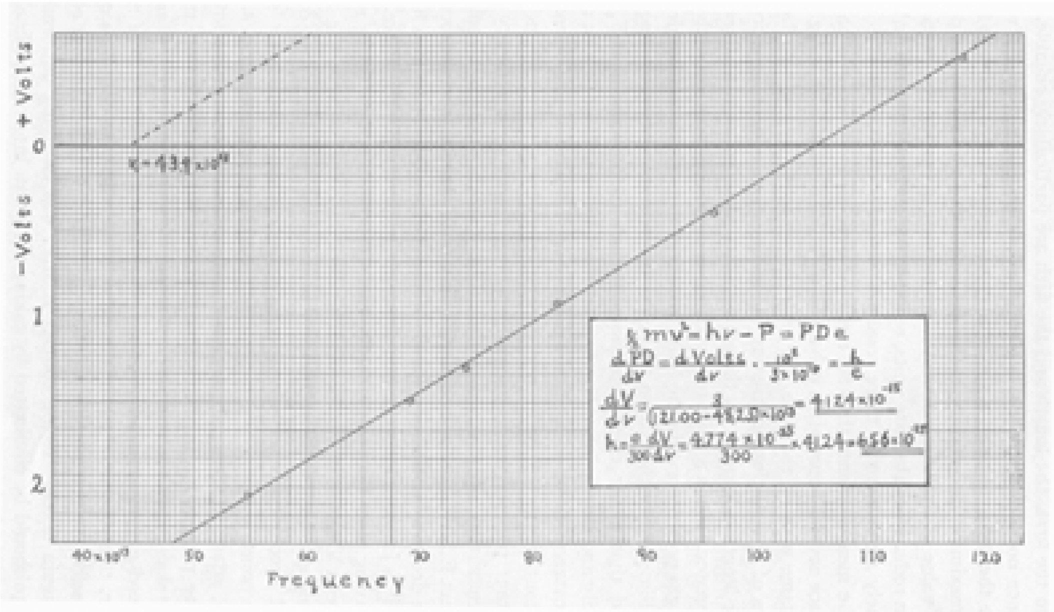


Fig. 2. Millikan's plot of the potential V required to stop photoelectrons from being ejected from sodium by radiation of frequency ν. The plot is a straight line of slope h/e, in agreement with Einstein's equation. *Source*: Millikan (1916), p. 373.

That left the theoretical interpretation of his experimental results. In his *Autobiography*, which he published in 1950 at the age of 82, Millikan (figure 3) included a chapter entitled "The Experimental Proof of the Existence of the Photon," in which he wrote:

This seemed to me, as it did to many others, a matter of very great importance, for it ... proved simply and irrefutably I thought, *that the emitted electron that escapes with the energy hv gets that energy by the direct transfer of hv units of energy from the light to the electron* and hence scarcely permits of any other interpretation than that which Einstein had originally suggested, namely that of the semi-corpuscular or photon theory of light itself [Millikan's italics].[18]

In Millikan's paper of 1916, however, which he published at the age of 48, we find a very different interpretation. There Millikan (figure 4) declares that Einstein's "bold, not to say reckless" light-quantum hypothesis "flies in the face of the thoroughly established facts of interference,"[19] so that we must

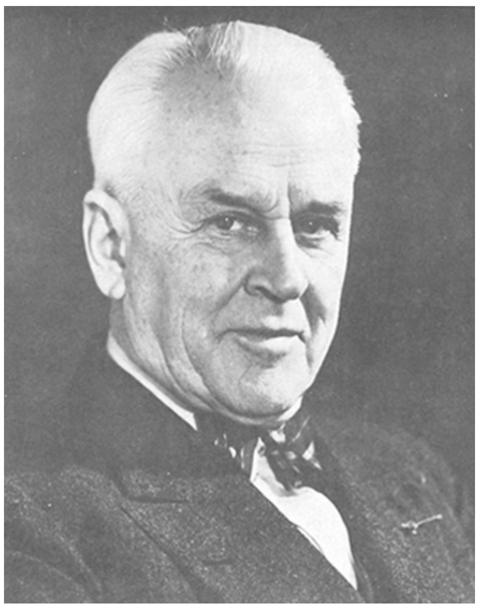


Fig. 3. Robert A. Millikan (1868-1953) at an advanced age. *Source*: Millikan (1950), frontispiece.

[18] Millikan (1950), pp. 101-102.
[19] Millikan (1916), p. 355.

Fig. 4. Robert A. Millikan (1868-1953) at the University of Chicago. *Source*: Kargon (1982), p. 45.

search for "a substitute for Einstein's theory."[20] Millikan's "substitute" theory was that the photosensitive surface must contain "oscillators of all frequencies" that "are at all times ... loading up to the value *hv*." A few of them will be "in tune" with the frequency of the incident light and thus will absorb energy until they reach that "critical value," at which time an "explosion" will occur and electrons will be "shot out" from the atom.

Millikan therefore fell completely in line with J.J. Thomson, Sommerfeld, and Richardson in proposing a classical, non-Einsteinian theory of the photoelectric effect in his paper of 1916. No one, in fact, made Millikan's views on Einstein's light-quantum hypothesis clearer than Millikan himself did in his book, *The Electron*, which he published in 1917, where he wrote:

> Despite ... the apparently complete success of the Einstein equation, the physical theory of which it was designed to be the symbolic expression is found so untenable that Einstein himself, I believe, no longer holds to it, and we are in the position of having built a very perfect structure and then knocked out entirely the underpinning without causing the building to fall. It [Einstein's equation] stands complete and apparently well tested, but without any visible means of support. These supports must obviously exist, and the most fascinating problem of modern physics is to find them. Experiment has outrun theory, or, better, *guided by erroneous theory*, it has discovered relationships which seem to be of the greatest interest and importance, but the reasons for them are as yet not at all understood [my italics].[21]

This, note, is the same man who thirty-four years later, in 1950, wrote that his experiments "proved simply and irrefutably I thought," that they scarcely permitted "any other interpretation than that which Einstein had originally suggested, namely that of the semi-corpuscular or photon theory of light."

[20] *Ibid.*, p. 385.
[21] Millikan (1917), p. 230.

Historians have a name for this, namely, "revisionist history." But this was by no means the first time that Millikan revised history as it suited him. The earliest instance I have found was his reproduction of a picture of J.J. Thomson in his study at home in Cambridge, England, sitting in a chair once owned by James Clerk Maxwell. Let us compare the original picture of 1899 with Millikan's reproduction of it in 1906 (figure 5). Note how Millikan has carefully etched out the cigarette in JJ's left hand. He presumably did not want to corrupt young physics students at the University of Chicago and elsewhere. In any case, this reflects what I like to call Millikan's philosophy of history: "If the facts don't fit your theory, change the facts."

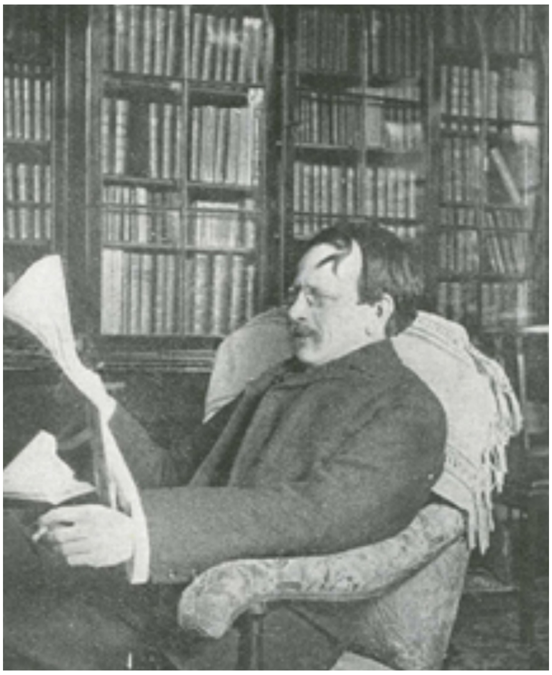
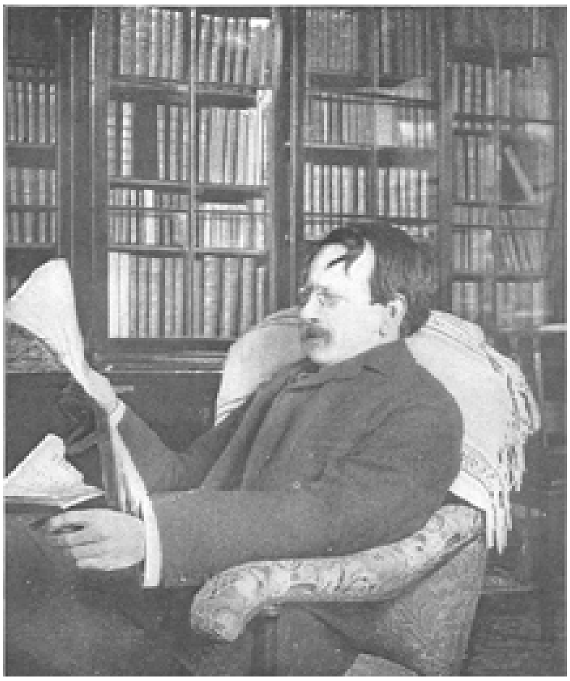


Fig. 5. J.J. Thomson (1856-1940) seated in a chair once owned by James Clerk Maxwell (1831-1879) as seen in a photograph of 1899. *Source*: Thomson, George Paget (1964), facing p. 53.



The same photograph as reproduced by Robert A. Millikan (1868-1953) in 1906. Note how carefully Millikan has etched out the cigarette in J.J.'s left hand. *Source*: Millikan and Gale (1906), facing p. 482.

Compton's Scattering Experiments[22]

Millikan's rejection of Einstein's light-quantum hypothesis characterized the general attitude of physicists toward it around 1916, when Arthur Holly Compton (figure 6) entered the field. Born in Wooster, Ohio, in 1892, Compton received his B.A. degree from the College of Wooster in 1913 and his Ph.D. degree from Princeton University in 1916. He then was an

[22] For a full discussion, see Stuewer (1975).

Fig. 6. Arthur Holly Compton (1892-1962) and his X-ray spectrometer. *Source*: Stuewer (1975), frontispiece.

Instructor in Physics at the University of Minnesota in Minneapolis for one year (1916-1917), a Research Engineer at the Westinghouse Electric and Manufacturing Company in Pittsburgh for two years (1917-1919), and a National Research Council Fellow at the Cavendish Laboratory in Cambridge, England, for one year (1919-1920) before accepting an appointment as Wayman Crow Professor and Head of the Department of Physics at Washington University in St. Louis in the summer of 1920, where he remained until moving to the University of Chicago three years later.

While at Westinghouse in Pittsburgh, Compton came across a puzzling observation that Charles Grover Barka made in 1917,[23] namely, that the mass-absorption coefficient of 0.145-Angstrom X rays in aluminum was markedly smaller than the Thomson mass-scattering coefficient whereas it should have been larger. To explain this, Compton eventually concluded that the X rays were being *diffracted* by electrons in the aluminum atoms, which demanded that the diameter of the electron be on the order of the wavelength of the incident X rays, say 0.1 Angstrom–in other words, nearly as large as the Bohr radius of the hydrogen atom, which was an exceedingly large electron. That was too much for Ernest Rutherford, who after Compton moved to the Cavendish Laboratory and gave a talk at a meeting of the Cambridge Philosophical Society, introduced Compton with the words: "This is Dr. Compton who is here to talk to us about the Size of the Electron. Please listen to him attentively, but you don't have to believe him."[24] Charles D. Ellis recalled that at one point in Compton's talk Rutherford burst out saying, "I will not have an electron in my laboratory as big as a balloon!"[25]

Compton, in fact, eventually abandoned his large-electron scattering theory to a considerable degree as a consequence of gamma-ray experiments that he carried out at the Cavendish Laboratory.[26] He found that (1) the intensity of the scattered γ rays was greater in

---

[23] Barkla and White (1917); Stuewer (1975), pp. 96-103.
[24] Quoted in Compton (1967), p. 29.
[25] Quoted in Eve (1939), p. 285.
[26] Stuewer (1975), pp. 135-158.

the forward than in the reverse direction; (2) the scattered γ rays were "softer" or of greater wavelength than the primary γ-rays; (3) the "hardness" or wavelength of the scattered γ rays was independent of the nature of the scatterer; and (4) the scattered γ rays became "softer" or of greater wavelength as the scattering angle increased.

We recognize these as exactly the characteristics of the Compton effect, but the question is: How did Compton explain these striking experimental results in 1919? The answer is that Compton, like virtually every other physicist at this time, also was completely convinced that γ rays and X rays were electromagnetic radiations of short wavelength. And after much thought, he hit on the idea that the electrons in the scatterer were tiny oscillators that the incident γ rays were propelling forward at high velocities, causing the electrons to emit a new type of secondary "fluorescent" radiation. The intensity of this secondary radiation would be peaked in the forward direction, and its increased wavelength was due to the Doppler effect.

Compton left the Cavendish Laboratory in the summer of 1920, taking a Bragg spectrometer along with him, because he knew that he wanted to carry out similar X-ray experiments at Washington University in St. Louis.[27] He obtained his first X-ray spectra in December 1921 by sending Molybdenum K_α X rays (wavelength $\lambda = 0.708$ A) onto a Pyrex scatterer and observing the scattered X rays at a scattering angle of about 90^o (figure 7). I emphasize that these are my plots of Compton's data as recorded in his laboratory notebooks, because I knew what I was looking for, namely, the small change in wavelength between the primary and secondary peaks, while Compton did not know what he was looking for, and–as his published paper makes absolutely clear–saw these two high peaks as the single primary peak, and the low peak at a wavelength of $\lambda' = 0.95$ A as the

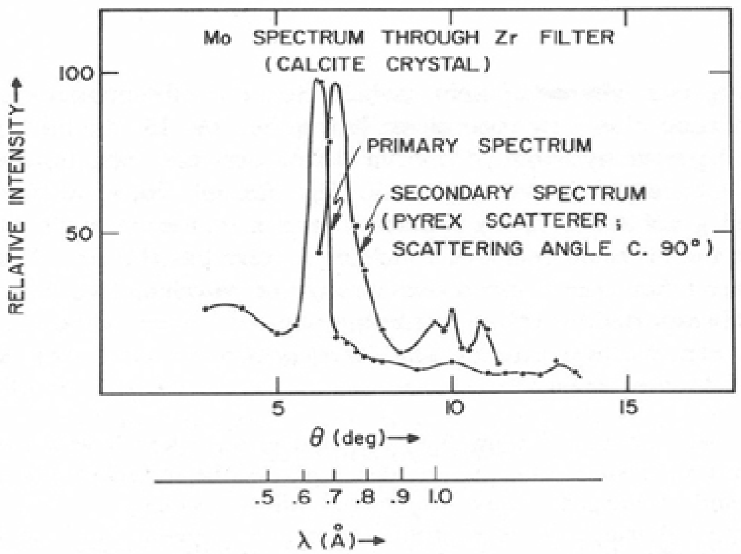


Fig. 7. Author's plot of Compton's spectra of December 1921 for Molybdenum K_α X rays scattered by Pyrex through an angle of about 90^o. *Source*: Stuewer, (1975), p. 187.

[27] Stuewer (1975), pp. 158-215.

secondary peak, whose wavelength thus was about 35% greater than that of the primary peak. Compton therefore concluded that the ratio of the wavelength λ of the primary peak to the wavelength λ' of the secondary peak was $\lambda/\lambda' = (0.708\ \text{A})/(0.95\ \text{A}) = 0.75$.

The question is: How did Compton interpret this experimental result theoretically? Answer: By invoking the Doppler effect, which at 90° is expressed as $\lambda/\lambda' = 1 - v/c$, where v is the velocity of the electron and c is the velocity of light. To eliminate the velocity v of the electron, Compton then invoked what he regarded as "conservation of energy," namely, that $½mv^2 = h\nu$, where m is the rest mass of the electron, so that $\lambda/\lambda' = 1 - v/c = 1 - \sqrt{[(2h\nu)/(mv^2)]}$, or substituting numbers, $\lambda/\lambda' = 1 - \sqrt{[(2(0.17\ \text{MeV})]/[(0.51\ \text{MeV})]} = 1 - 0.26 = 0.74$. Who could ask for better agreement between theory and experiment? I think this is a wonderful historical example of a *false* theory being confirmed by *spurious* experimental data.

By October 1922, however, Compton knew that the change in wavelength was not 35% but only a few percent.[28] By then he had sent Molybdenum K_α X rays onto a graphite (carbon) scatterer and observed the scattered X rays at a scattering angle of 90° (figure 8), finding that the wavelength λ' of the secondary peak was $\lambda' = 0.730$ A, so that now $\lambda/\lambda' = (0.708\ \text{A})/(0.730\ \text{A}) = 0.969$.

The question again is: How did Compton interpret this experimental result theoretically? Answer: By again invoking the Doppler effect, namely, that at 90° $\lambda/\lambda' = 1 - v/c$, where now to eliminate the velocity v of the electron, Compton invoked what he regarded as "conservation of momentum," namely, that $mv = h/\lambda$, so that $\lambda/\lambda' = 1 - v/c = 1 - h/mc\lambda$, which is exactly the equation he placed to the right of his spectra. Rewriting it as $\lambda/\lambda' = 1 - h\nu/mv^2$ and

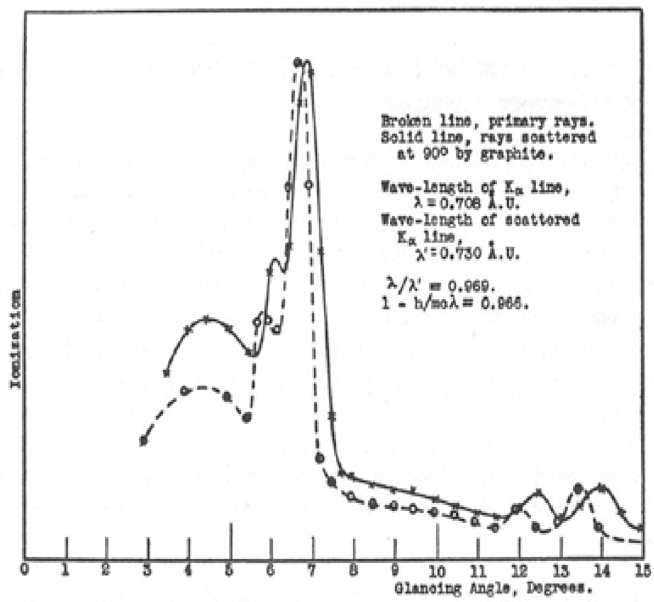


Fig. 8. Compton's spectra of October 1922 for Molybdenum K_α X rays scattered by graphite (carbon) through an angle of 90°. *Source*: Compton (1922), p. 16; Shankland (1973), p. 336.

28 Compton (1922).

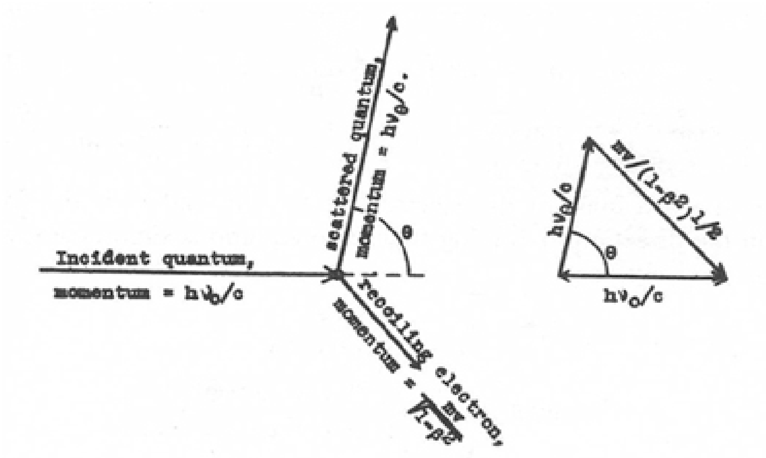


Fig. 9. Compton's quantum theory of scattering of 1922. A primary X-ray quantum of momentum $h\nu_o/c$ strikes an electron and scatters through an angle θ, producing a secondary X-ray quantum of momentum $h\nu_\theta/c$ and propelling the electron away with a relativistic momentum of $mv/\sqrt{(1-\beta^2)}$, where m is the rest mass of the electron and $\beta = v/c$. *Source*: Compton (1923), 486; Shankland (1975), p. 385.

substituting numbers, he found that $\lambda/\lambda' = 1 - (0.17 \text{ MeV})/(0.51 \text{ MeV}) = 1 - 0.034 = 0.966$. Again, who could ask for better agreement between theory and experiment? I think this is a wonderful historical example of a *false* theory being confirmed by *good* experimental data.

Compton put everything together one month later, in November 1922, aided materially by discussions he had had with his departmental colleague G.E.M. Jauncey.[29] He now assumed that an X-ray quantum strikes an electron in a billiard-ball collision process in which *both* energy *and* momentum are conserved.[30] He drew his famous vector diagram (figure 9) and calculated the change in wavelength

$\Delta\lambda = \lambda_\theta - \lambda_o = (h/mc)(1 - \cos\theta) = h/mc$

between the incident and scattered light quantum for a scattering angle of $\theta = 90^o$. What experimental support did Compton now cite for his new quantum theory of scattering? Note that the spectra he published in his paper of May 1923 (figure 10) were *identical* to those he had published in October 1922. Only his theoretical calculation to their right had changed. As every physicist knows,

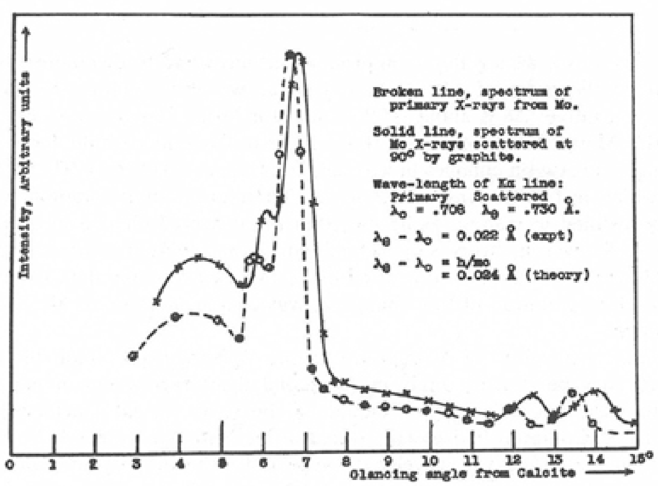


Fig. 10. Compton's spectra of 1923 for Molybdenum K_α X rays scattered by graphite (carbon) through an angle of 90^o. Note that they are identical to those he published in October 1922 (Fig. 8), but that he now calculated the change in wavelength $\lambda_\theta - \lambda_o = h/mc$ between the secondary and primary light quantum on the basis of his new quantum theory of scattering. *Source*: Compton (1923), 495; Shankland (1975), p. 394.

[29] Jenkin (2002), pp. 328-330.
[30] Compton (1923a).

theories come and go, but good experimental data never dies!

We see that Compton's discovery of the Compton effect was the culmination of six years of experimental and theoretical research, between 1916 and 1922. His thought, in other words, evolved along with his own experimental and theoretical work, in a largely autonomous fashion.

There is no indication, in particular, that Compton ever read Einstein's light-quantum paper of 1905. In fact, Compton neither cited Einstein's paper in his own paper of 1923, nor even mentioned Einstein's name in it.

This is in striking contrast to Peter Debye (figure 11), who proposed the identical billiard-ball quantum theory of scattering independently and virtually simultaneously,[31] and who explicitly stated in his paper that his point of departure was Einstein's concept of "needle radiation." The chronology of Compton's and Debye's work is instructive, as follows:

November 1922: Compton reported his discovery to his class at Washington University.

December 1 or 2, 1922: Compton reported his discovery at a meeting of the American Physical Society in Chicago.

December 6, 1922: Compton submitted another paper, on the total-internal reflection of X rays, to the *Philosophical Magazine*.[32]

December 10, 1922: Compton submitted his paper on his quantum theory of scattering to *The Physical Review*.

March 15, 1923: Debye submitted his paper on the quantum theory of scattering to the *Physikalische Zeitschrift*.

April 15, 1923: Debye's paper was published in the Physikalische Zeitschrift.

May 1923: Compton's paper was published in *The Physical Review*.

Fig. 11. Peter Debye (1884-1966) in an undated photograph but probably from the 1920s. *Credit*: American Institute of Physics Emilio Segrè Visual Archives, Fankuchen Collection.

---

[31] Debye (1923).
[32] Compton (1923b).

Now, there is nothing more wave-like than total-internal reflection, and there is nothing more particle-like than the Compton effect. We thus see that within the space of one week, between December 6 and December 10, 1922, Compton submitted for publication conclusive experimental evidence for *both* the wave *and* the particle nature of X rays. I take this to be symbolic of the profound dilemma that physicists faced at this time over the nature of radiation.

Further, as seen in the above chronology, Debye's paper actually appeared in print one month before Compton's, which led some physicists, especially European physicists, to refer to the discovery as the Debye effect or the Debye-Compton effect. Fortunately for Compton, Arnold Sommerfeld was in the United States at this time as a visiting professor at the University of Wisconsin in Madison, and because he knew that Compton had priority in both the experiment and the theory, after he returned home to Munich, Germany, he was instrumental in persuading European physicists that it should be called the Compton effect. Debye himself later insisted that it should be called the Compton effect, saying that the physicist who did most of the work should get the name.[33]

Aftermath

Compton's experimental results, however, did not go unchallenged.[34] In October 1923 George L. Clark, a National Research Council Fellow working in William Duane's laboratory at Harvard University, announced--with Duane's full support--that he could not obtain the change in wavelength that Compton had reported.

This was a serious experimental challenge to Compton's work, which was not resolved until December 1924 when Duane (figure 12) forthrightly admitted at a meeting of the American Physical Society that their experiments were faulty.[35]

Fig. 12. William Duane (1872-1935). *Source*: Bridgman (1936), frontispiece.

[33] Quoted in Kuhn and Uhlenbeck (1962), p. 12
[34] Stuewer (1975), pp. 249-273.
[35] Bridgman (1936), p. 32.

That resolved the experimental question, but the theoretical question still remained open. Niels Bohr (figure 13) challenged Compton's quantum theory of scattering directly in early 1924.

Bohr, in fact, had never accepted Einstein's light quanta. Most recently, in his Nobel Lecture in December 1922, Bohr had declared:

> In spite of its heuristic value, ... the hypothesis of light-quanta, which is quite irreconcilable with so-called interference phenomena, is not able to throw light on the nature of radiation.[36]

Two years later, in 1924, Bohr and his assistant Hendrik A. Kramers adopted John C. Slater's concept of virtual radiation and published, entirely without Slater's cooperation, the Bohr-Kramers-Slater paper[37] whose essential feature was that energy and momentum were conserved only statistically in the interaction between an incident light quantum and an electron in the Compton effect. As C.D. Ellis remarked, "it must be held greatly to the credit of this theory that it was sufficiently precise in its statements to be disproved definitely by experiment."[38]

Hans Geiger and Walter Bothe in Berlin were the first to disprove the BKS theory, in coincidence experiments that they reported on April 18 and 25, 1925.[39] Then Compton (now at Chicago) and his student Alfred W. Simon disproved the BKS theory in even more conclusive coincident experiments that they reported on June 23, 1925. Even before that, however, on April 21, 1925, just after Bohr learned about the Bothe-Geiger results, he added a postscript to a letter to Ralph H. Fowler in Cambidge: "It seems therefore that there is nothing else to do than to give our revolutionary efforts as honourable a funeral as possible."[40] Of course, as Einstein said in a letter of August 18, 1925, to his friend Paul Ehrenfest: "We both had no doubts about it."[41]

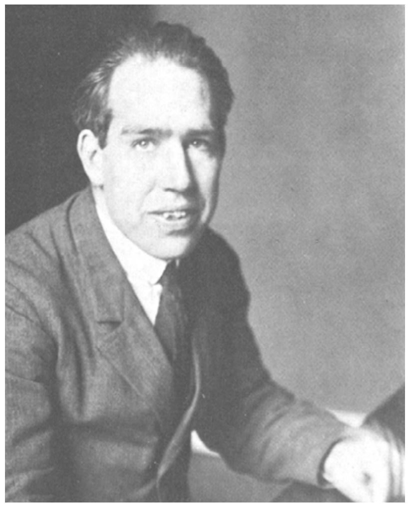


Fig. 13. Niels Bohr (1885-1962) at his desk in the 1920s. *Source*: Nielsen (1976), frontispiece.

[36] Bohr (1923 [1922]), p. 4; 14; 470.
[37] Bohr, Kramers, and Slater (1924).
[38] Ellis (1926).
[39] Bothe and Geiger (1925a, 1925b).
[40] Bohr to Fowler, April 21, 1925. In Stolzenburg (1984), pp. 81-84; quote on p. 82.
[41] Einstein to Ehrenfest, August 18, 1925. Quoted in Klein (1970), p. 35.

References

Barkla, C.G. and White, M.P. (1917). "Notes on the Absorption and Scattering of X-rays and the Characteristic Radiation of J-series." *Philosophical Magazine* **34**, 270-285.

Beck, Anna, transl. (1989). *The Collected Papers of Albert Einstein.* Vol. 2. *The Swiss Years: Writings, 1900-1909.* Princeton: Princeton University Press.

Beck, Anna, transl. (1995). *The Collected Papers of Albert Einstein.* Vol. 5. *The Swiss Years: Correspondence, 1902-1914.* Princeton: Princeton University Press.

Bohr, Niels. (1923 [1922]). "The structure of the atom." *Nature* **112**, 1-16 [Nobel Lecture, December 11, 1922]. In Nobel Foundation (1965), pp. 7-43; Nielsen (1977), pp. 467-482.

Bohr, N., Kramers, H.A., and Slater, J.C. (1924). "The Quantum Theory of Radiation." *Philosophical Magazine* **97**, 785-802. In Stolzenburg (1984), pp. 101-118.

Bothe, W. and Geiger, H. (1925a). "Experimentelles zur Theorie von Bohr, Kramers und Slater." *Die Naturwissenschaften* **13**, 440-441.

Bothe, W. and Geiger, H. (1925b). "Über das Wesen des Comptoneffekts: ein experimenteller Beitrag zur Theorie der Strahlung." *Zeitschrift für Physik* **32**, 639-663.

Bridgman, P.W. (1936). "Biographical Memoir of William Duane 1872-1935." *National Academy of Sciences Biographical Memoirs* **18**, 23-41.

Buchwald, Jed Z. (1994). *The Creation of Scientific Effect: Heinrich Hertz and Electric Waves.* Chicago: University of Chicago Press.

Compton, Arthur H. (1922). "Secondary Radiations produced by X-Rays, and Some of their Applications to Physical Problems," *Bulletin of the National Research Council* **4**, Part 2 (October)

Compton, Arthur H. (1923a). "A Quantum Theory of the Scattering of X-Rays by Light Elements," *Physical Review* **21**.

Compton, Arthur H. (1923b). "The Total Reflexion of X-Rays." *Philosophical Magazine* **45**, 1121-1131. In Shankland (1973), pp. 402 412.

Compton, Arthur H. (1967). "Personal Reminiscences." In Johnston (1967), pp. 3-52.

Debye, P. (1923). "Zerstreuung von Röntgenstrahlen und Quantentheorie." *Physikalische Zeitschrift* **24**, 161-166. Translated in Debye (1954), pp. 80-88.

Debye, P. (1954). *The Collected Papers of Peter J.W. Debye.* New York: Interscience.

Duncan, Anthony and Janssen, Michel. (2007). "Pascual Jordan's resolution of the conundrum of the wave-particle duality of light." Preprint submitted to Elsevier Science, 53 pp. September 18.

Einstein, A. (1905). "Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt." *Annalen der Physik* **17**, 132-148. In Stachel (1989), pp. 150-166; Beck (1989), pp. 86-103.

Einstein, A. (1909a). "Zum gegenwärtigen Stand des Strahlungsproblems." *Physikalische Zeitschrift* **10**, 185-193. In Stachel (1989), pp. 542-550; Beck (1989), pp. 357-375.

Einstein, A. (1909b). "Über die Entwickelung unserer Anschauungen über das Wesen und die Konstitution der Strahlung." *Verhandlungen der Deutschen Physikalischen Gesellschaft* **7**, 482-500; *Physikalische Zeitschrift* **10**, 817-826 (with "Discussion"). In Stachel (1989), pp. 564-582, 585-586; Beck (1989), pp. 379-398.

Ellis, C.D. (1926). "The Light-Quantum Theory." *Nature* **117**, 896.

Eve, A.S. (1939). *Rutherford: Being the Life and Letters of the Rt Hon. Lord Rutherford, O.M.* New York: Macmillan and Cambridge: Cambridge University Press.

Friedrich, W., Knipping, P., and Laue, M. (1912). "Interferenz-Erscheinungen bei Röntgenstrahlen." *Bayerische Akademie der Wissenschaften, Sitzungsberichte*, 303-322. In Laue (1961), pp. 183-207.

Hoffmann, Banesh (1972). *Albert Einstein: Creator and Rebel*. New York: The Viking Press.

Jenkin, John (2002). "G.E.M. Jauncey and the Compton Effect." *Physics in Perspective* **2**, 320-332.

Johnston, Marjorie ed. (1967). *The Cosmos of Arthur Holly Compton*. New York: Alfred A. Knopf.

Kargon, Robert H. (1982) *The Rise of Robert Millikan: Portrait of a Life in American Science*. Ithaca and London: Cornell University Press.

Klein, Martin J. (1963). "Einstein's First Paper on Quanta." *The Natural Philosopher* **2**, 57-86.

Klein, Martin J. (1964). "Einstein and the Wave-Particle Duality." *The Natural Philosopher* **3**, 1-49.

Klein, Martin J. (1970). "The First Phase of the Bohr-Einstein Dialogue." *Historical Studies in the Physical Sciences* **2**, 1-39.

Klein, Martin J., Kox, A.J., and Schulmann, Robert, ed. (1993). *The Collected Papers of Albert Einstein.* Vol. 5. *The Swiss Years: Correspondence, 1902-1914.* Princeton: Princeton University Press.

Kuhn, T.S. and Uhlenbeck, G.E. (1962). Interview with Peter Debye, Archive for the History of Quantum Physics, May 3.

Laue, M. (1912). "Eine quantitaive Prüfung der Theorie für die Interferenz-Erscheinungen bei Röntgenstrahlen." *Bayerische Akademie der Wissenschaften, Sitzungsberichte*, 363-373. In Laue (1961), pp. 208-218.

Laue, Max von. (1961). *Gesammelte Schriften und Vorträge.* Band I. Braunschweig: Friedr. Vieweg & Sohn.

Lenard, P. (1902). "Über die lichtelektrische Wirkung." *Annalen der Physik* **8**, 149-198. In Lenard (1944), pp. 251-290.

Lenard, P. (1944). *Wissenschaftliche Abhandlungen.* Band 3. *Kathodenstrahlen, Elektronen, Wirkungen Ultravioletten Lichtes.* Leipzig: Verlag von S. Hirzel.

Millikan, R.A. (1916). "A Direct Photoelectric Determination of Planck's '*h*'." *Physical Review* **7**, 355-388.

Millikan, Robert Andrews. (1917). *The Electron: Its Isolation and Measurement and the Determination of Some of its Properties.* Chicago: University of Chicago Press.

Millikan, Robert A. (1950). *The Autobiography of Robert A. Millikan.* New York: Prentice-Hall.

Millikan, Robert Andrews and Gale, Henry Gordon (1906). *A First Course in Physics*. Boston: Ginn & Company.

Nielsen, J. Rud, ed. (1976). *Niels Bohr Collected Works.* Vol. 3. *The Correspondence Principle (1918-1923)*. Amsterdam: North-Holland.

Nielsen, J. Rud, ed. (1977). *Niels Bohr Collected Works.* Vol. 4. *The Periodic System (1920-1923)*. Amsterdam: North-Holland.

Nobel Foundation. (1965). *Nobel Lectures including Presentation Speeches and Laureates' Biographies: Physics 1922-1941*. Amsterdam: Elsevier.

Shankland, Robert S., ed. (1973). *Scientific Papers of Arthur Holly Compton: X-Ray and Other Studies.* Chicago: University of Chicago Press.

Stachel, John, ed. (1989). *The Collected Papers of Albert Einstein.* Vol. 2. *The Swiss Years: Writings, 1900-1909.* Princeton: Princeton University Press.

Stolzenburg, Klaus, ed. (1984). *Niels Bohr Collected Works.* Vol. 5. *The Emergence of Quantum Mechanics (Mainly 1924-1926).* Amsterdam: North-Holland.

Stuewer, Roger H. (1971). "Hertz's Discovery of the Photoelectric Effect." *Proceedings of the XIIIth International Congress in the History of Science*, Section VI. Moscow, pp. 35-43.

Stuewer, Roger H. (1975). *The Compton Effect: Turning Point in Physics.* New York: Science History Publications.

Thomson, George Paget (1964). J.J. Thomson and the Cavendish Laboratory in his Day. London: Nelson.