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Article

Light Quanta: the Maturing of a Concept by the Stepwise Accretion of Meaning

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Abstract: I will begin by identifying 12 layers of meaning of the concept of light quanta as it is understood today. The main part of this contribution will then discuss some of the earlier layers. I will also briefly discuss the extreme skepticism with which the concept of light quanta was received between 1905 and 1922 and close with a thesis on what makes Einstein's thinking so exceptional.

Keywords: Photons, Quantum mechanics, Einstein

1 Introduction

Today's understanding of light quanta encompasses the following features:

1. particle-like, localized
2. propagation with finite velocity
3. equality of velocity of light for all colors / frequencies
4. light transmits energy E
5. light transmits momentum $p = E/c$ (leading to radiation pressure)
6. energy E of light is correlated with its frequency ν: $E \sim \nu$?
7. energy E of each light quantum is quantized: $E = h\nu$?
8. emission and absorption of light quanta by matter
9. wave-particle-dualism

10. light quanta transmit angular momentum; their spin is ± 1.

11. indistinguishability of light quanta with equal E and equal spin

12. the statistics of these light quanta is that of bosons.

All these layers of meaning are automatically present when physicists today hear the cue word *light quantum*. Many readers might even have automatically replaced this with the term 'photons' nowadays in use. This brings me to the first point of this paper: instead of departing from the assumption that the concept of 'light quanta' had suddenly been discovered by Einstein exactly 100 years ago, I will argue that the concept we know today *matured* in a stepwise enrichment of layers of meaning. Thus, the term 'photon' was first introduced as late as the end of 1926 by Gilbert Lewis, that is roughly 20 years after Einstein's famous paper from 1905 and one year after the discovery of electron spin in 1925. The other layers of meaning of the word 'light quanta' also have complex histories of their own, extending variously back into the past. Layer 1 will take us to a miniature comparison of Einstein with Newton; layer 7 will include contrasting Einstein against Planck, and layer 6 will consider Philipp Lenard's different interpretation of the photoelectric effect.

2 Corpuscularity or particle characteristics

We find particle theories of light, in the broadest sense of the word, as far back as the atomists of Ancient Greece, but Sir Isaac Newton was the first to conceive a more developed model of this type. His early papers in the Royal Society's *Philosophical Transactions* do their best *not* to reveal his basic conception of light as a corpuscle. Nevertheless, his *Principia* from 1687 as well as the queries in his *Opticks* from 1704 provide clear hints at this projectile model. His *mathematical principles of natural philosophy*, for instance, derive light diffraction from a stronger attraction of light particles to the denser medium, and in query 29 of his *Opticks* he asks[1]:

> "Are not the Rays of Light very small Bodies emitted from shining Substances?"

Many people tried to nail him down on this projectile model of light (such as his most strident critic Robert Hooke) but Newton replied with his **distinction between facts and hypotheses**.[2]

> "*that light is a body* [...], it seems, is taken for my *Hypothesis*. 'Tis true, that from my Theory I argue the *Corporeity* of Light; but I do it without any absolute positiveness, as the word *perhaps* intimates; and make it at most but a very plausible *consequence* of the Doctrine, and not a fundamental *Supposition*,..."

[1] Newton (1730), query 29, p. 370; cf. also Newton (1687), sect. XIV, paragraph 141 ff.

[2] Newton (1672), p. 5086, in his reply to Hooke. Reprint together with Hooke's attacks in Cohen (1958), quote from p. 118.

The reason for this caution was clear: Newton knew perfectly well that he could not prove without an element of doubt that the corpuscular model of light was right. Other interpretations were still possible:[3]

> "But I knew, that the *Properties*, which I declar'd of *Light*, were in some measure capable of being explicated not only by that, but by many other Mechanical *Hypotheses*. And therefore I chose to decline them all, and to speak of Light in general terms, considering it abstractedly, as something or other propagated every way in straight lines from luminous bodies, without determining, what that Thing is."

Unlike the Cartesians, Newton did not want to hypothesize out of the blue, which did not prevent him from frequently making *heuristic* use of such hypotheses and conceptual models. But the findings from his prism experiments about white light being composed of the different colors was not supposed to be hampered at all by such speculative models. That was why he confined his later essays to the somewhat phenomenological theory of white light composed of colored light: this was controversial enough as it was.

Newton's cautious wording in his essays on light is remarkably similar to Einstein's in his paper from 1905 on 'a heuristic point of view'. Einstein writes: "monochromatic radiation of low density... behaves *as if* it were composed of mutually independent energy quanta."[4] This fictionalistic as-if conjunctive produces the same **intellectual reserve** with which Newton enveloped his projectile model. Just like Newton, Einstein also had a more urgent statement to defend, a statement that was likewise more phenomenological than the light-quantum model: namely, the equation $E = h\nu$. The underlying *model* of light was pushed into the background.

This rhetorical pose, assumed out of caution, does not weaken the underlying mental model heuristically in any way. In both cases (Newton and Einstein) it still shines through the relevant passages, while allowing the actors to avoid being pinned down to it. This coyness was for understandable reasons, considering the extreme skepticism with which the light quantum was received in 1905.

Some manuscripts have been preserved that reveal in how much detail Newton thought of his 'light globuli' in hydromechanical terms. It is most developed in his notebook from 1664-65 *Questiones quæ dam philosophicæ*, in which we find this sketch of a *Globulus of light* together with commentary.

This spherically shaped light corpuscle is enveloped in what he called "subtile matter", or luminous aether. The motion of the globulus of light from left to right causes the luminous aether to swirl around it (on the right a compression zone with corresponding resistance, and on the left a vortex zone. Newton assumed that this produced a kind of backward pressure that pushed the light corpuscle forward.

[3] Newton (1672), p. 5087, resp. Cohen (1958), p. 119; orthography, punctuation and emphasis, as in the former quote, original.

[4] Einstein (1905a), p. 161, my emphasis.

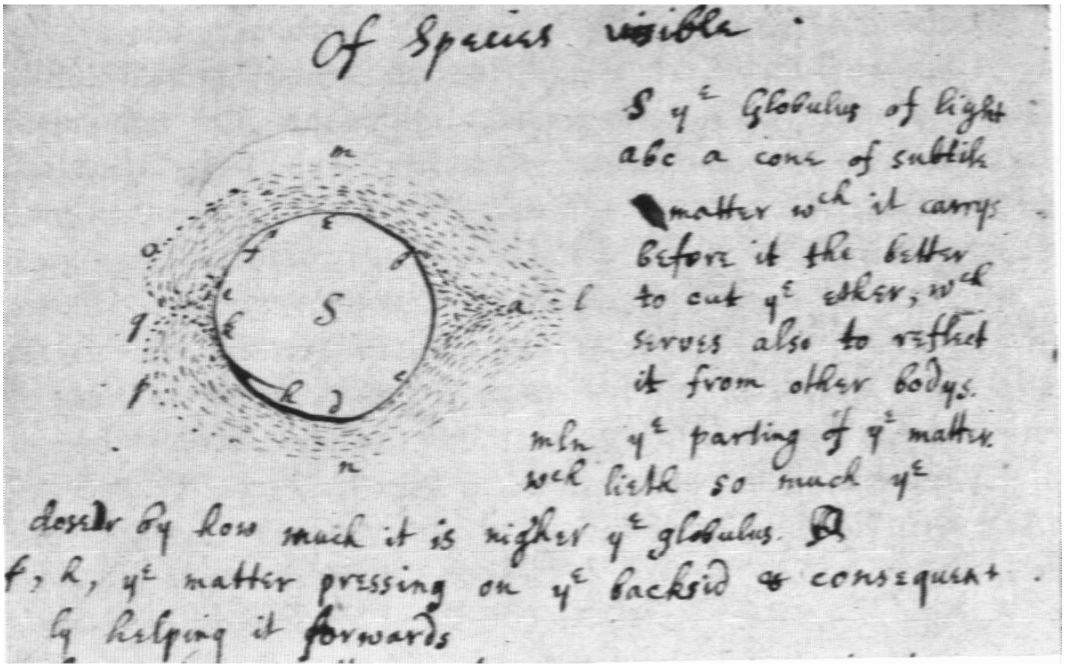

Figure 1: From Newton's *Questiones quædam philosophicæ* from 1664/65, call no. 34 104, in the edition of Newton (1983), pp. 384 f.

One could argue that quite some time had elapsed since the heyday of Newton's projectile model of light. It was not probable that Einstein would have developed his extensions directly from it. He did not need to either. Just two years before his own paper from 1905, so famous today, Joseph John Thomson in Cambridge had retrieved these findings for Einstein.

J.J. Thomson's Silliman Lectures as guest lecturer at Yale University in 1903 on *Electricity and Matter* were already translated into German by 1904 and available to Einstein in Berne. In these lectures, J.J. Thompson speculated about corpuscular localized field quanta in an effort to explain anomalies in the propagation of X-rays, which had been discovered by Röntgen in late 1895. These anomalies were:

1. the extremely directed and point-like effects of such hard rays, then referred to as "needle" radiation

2. the fact that its intensity did not diminish as $1/r^2$ but remained almost the same even over longer distances, if one disregarded occasional ionization of directly hit gas molecules.

In 1950 Robert Millikan was still speaking of the "Thomson-Planck-Einstein conception of localized radiant energy (i.e., the corpuscular or photon conception of light)" instead of: 'Einstein's light quanta'. Speculations about the corpuscularity of specific types of radiation are thus older than Einstein's "heuristic point of view" from 1905.[5] There is no analogous sketch by Einstein depicting his conception of the light quantum as clearly as Newton's and J.J. Thomson's. That is not to say that Einstein's model was any less sophisticated. It was just more abstract. But he also considered the *corpuscularity* of light in connection with its *propagation velocity*. Newton's surrounding aether becomes for Einstein the surrounding field of radiation of other particles of light (more on this later). The constancy of its propagation velocity was, as we know, one of the axioms of his paper which appeared three months later in the *Annalen der Physik*: 'On the Electrodynamics of Moving Bodies'.

Before Einstein arrived at his postulate of the constancy of light velocity in a vacuum, he carefully considered its dependence on the velocity of its emitter, as is suggested in the projectile theory of light. We know this from his correspondence with Paul Ehrenfest as well as from his comments on contemporary papers by Walter Ritz, who worked on exactly such types of emission theories. Einstein's postulate of a constant velocity of light in all inertial systems was a direct consequence of the failure of emission theories.[6] This is a concealed but interesting link between the famous papers from 1905.[7] "Turn the problem into a postulate, that's how you get by", Einstein later joked.

3 Energy and momentum transfer (radiant pressure)

Layers 4 and 5 of the mental model of light quanta have a long history extending far back:[8]

- Kepler 1608 on the direction of comet tails
- Homberg 1708 on objects in the focus of burning glasses
- Abraham Bennet 1792 experiments in an evacuated glass container
- around 1876: discussions on Crookes's light mill
- Lebedev 1901: 1st experimental confirmation of radiation pressure (still with large systematic error >10%)
- Nichols & Hull 1903: improved experimental confirmation

[5] Millikan (1960), p. 102 (for criticism of this text see below footnote 15), referring back to Thomson (1904) (quote p. 111); cf. Wheaton (1983) and McCormmach (1967).

[6] See, e.g., Martinez (2004) and Norton (2004), esp. pp. 57 ff. and further primary literature cited there, e.g., Einstein's letter to Ehrenfest from 1912.

[7] On another hidden link, the similar relativistic transformation of energy and frequency, see Pais (1982), p. 408, Klein (1967) and Rynasiewicz (2005), p. 74.

[8] On the following see, e.g., Homberg (1708), p. 21. Cf. Worrall (1982), particularly p. 141 for hints on similar experiments by Nicolas Hartsoeker (1696), de Mairan (1747) and others.

When Einstein submitted his paper in 1905, the existence of radiation pressure had just recently been established by experiments of the Russian Lebedev and the Americans Nichols and Hull.[9] The decisive papers fall exactly in the period when Einstein was studying articles in the *Annalen der Physik* among other physics journals during his leisure time as an examiner of the Swiss Patent Office. Remarks in his papers of 1905 and 1909 show that he knew about the "just recently experimentally confirmed light pressure, which plays such an important role in the theory of radiation."[10]

4 Proportionality between energy and frequency

But Einstein could not find everything in the scientific literature. If he had relied on that he would have missed the correlation between the energy and frequency of light. Both Lebedev and Nichols & Hull went on the assumption from classical electrodynamics that the energy of light was always proportional to its intensity I: $I \sim E \sim H^2 + D^2$. Lebedev explicitly writes in 1901: "These pressure forces of light are directly proportional to the impinging amount of energy and *independent* of *the color of light*." Nichols and Hull thought they were able to confirm this two years later (1903), because their measurements of the light pressure initially suggested (independently of the choice of filters) a frequency-independent energy proportional to the light's intensity.[11] This false conclusion is generally concealed in the professional folklore.

Einstein's extraordinary sense for the validity of experimental results saved him from being led astray. Instead of just relying on this one experimental strand, he linked experimental results from the most disparate areas of scientific inquiry. Interweaving these individual strands, each one of which might have led to a dead end if followed on its own, taken together yielded a dense web.

> "It does indeed appear to me that the observations on "black-body radiation," photoluminescence, the generation of cathode rays from ultraviolet light [photoelectric effect] and other *groups of phenomena* concerning the generation or transformation of light would appear better comprehensible under the assumption that the energy of light was discontinuously distributed."[12]

[9] See Lebedew (1901), Nichols/Hull (1903) and the later corrections and further improvements in Bell/Green (1933) and Hull/Bell/Green (1934).

[10] Einstein (1905b), here p. 915, resp. Einstein (1909a), resp. Cassidy et al. (1990), p. 300 and 565, quote Einstein (1909a), p. 483.

[11] Lebedew (1901), fn. 8 on p. 458 and Nichols/Hull (1903), p. 104: "it appears that the radiation pressure depends only upon the intensity of the radiation and is independent of the wave-length." Erich Ladenburg was the first to demonstrate a frequency dependency of the energy of UV radiation in 1907 (probably without knowing of Einstein's paper of 1905, which he did not quote); but he still assumed that the constant of proportionality varies with the emitting material: see Ladenburg (1907). Joffé (1907) then linked Einstein's theoretical paper and these experimental results. On the transmission of energy by light see also Einstein to Conrad Habicht, mid-1905, Klein/Kox/Schulman (1993), Doc. 28, p. 33.

[12] Einstein (1905a), p. 133.

Let's take a closer look at one of these strands, the photoelectric effect. Since 1887 it was known that when bombarded with ultraviolet light, a cathode in an evacuated tube released negatively charged electricity, so-called cathode rays.[13] Philipp Lenard had established in 1902 that the amount of charge released by the photoelectric effect was independent of the external electric potential. From this he concluded "that the light causes the formation of the rays not outside but inside the body, where it is also absorbed in a way that the negative electricity quanta are set into propagating motion at specific starting velocities,..."[14] There were two possible ways to model this emission process:

1. The kinetic energy of released cathode rays (or as some people, other than Lenard, started to call these "electricity quanta") originate from absorbed ultraviolet radiation.

2. UV radiation acts only as a trigger that releases charges.

Lenard's experiments revealed that the beginning velocities of cathode rays (electrons) are largely independent of the light intensity. That is why he excluded the first model and decided on the second option to model this process. Lenard's **trigger hypothesis** states that[15]

> "the initial velocities of the emitted [charge] quanta do not originate at all from the luminous energy but from powerful motions already existing within the atoms even before exposure to the light, so the resonance motions [between UV radiation and the atoms] only act as a trigger [...] for motions that then would have to exist permanently at full velocity *within* the atoms of the body."

Hence, according to Lenard, the kinetic energy of cathode rays did *not* originate from light. Einstein did not find Lenard's trigger hypothesis convincing.
Einstein's light quantum hypothesis suggested a different model for the photoelectric effect (more along the lines of Lenard's rejected option no. 1)[16]:

> "According to the interpretation that the excited light is composed of energy quanta of energy $(R/N)\beta\nu$, the generation of cathode rays by light can be understood in the following way. Energy quanta penetrate into the surface layer of the body and their energy is transformed at least in part into the kinetic energy of electrons. [...] Furthermore, it has to be assumed that upon leaving the body each electron must expend work P (characteristic of the body)".

[13] Hallwachs (1907) and further primary sources, cited in Wheaton (1983) and Wiederkehr (1973).

[14] See Lenard (1902), quote from p. 149; cf. also Wheaton (1978) on Lenard's model of the effect, esp. p. 300 on his interpretation of charge quanta as 'free electricity', as "latent motion of the æther"; Stuewer (1970) and further sources listed there.

[15] Lenard (1902), pp. 170, 150.

[16] Einstein (1905a), pp. 145 f.

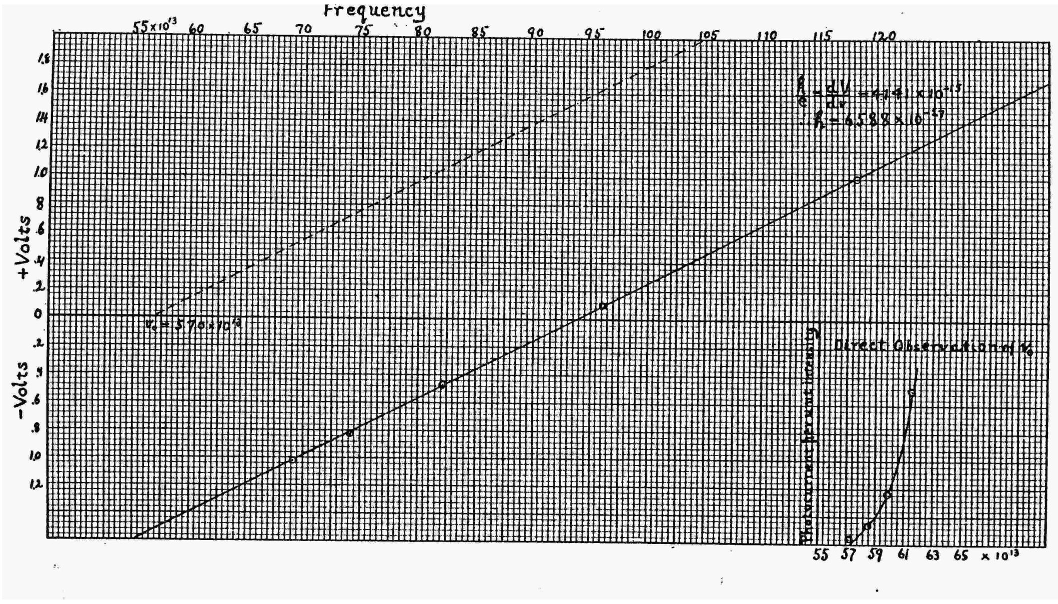

Figure 2: Diagram from Millikan (1916), p. 25.

The kinetic energy of the released electrons was therefore equal to the energy of the impinging radiation minus the emitting work P. It was determinable by raising the positive potential to the point that all released electrons could no longer traverse the opposite potential field, hence leading to a vanishing photo-electric current. This limiting potential Π times the elementary charge of these 'electricity quanta' was thus equal to the maximum kinetic energy $= h\nu - P$. Experimentally determining this limiting potential as a function of the frequency of impinging monochromatic radiation yielded the possibility of determining its energy as a function of the frequency.

> "If the derived formula is correct, then [the positive limiting potential] Π must, as a function of the frequency of the excited light, be a straight line [...], whose slope is independent of the nature of the substance under examination."[17]

Lenard had not even sought this frequency dependence according to his own model. He had found a slight dependence of the limiting potential on the type of light used, but had not followed up this hint. Ten years had to go by before Millikan was able to verify Einstein's prediction experimentally beyond doubt. We shouldn't forget that Millikan had expressly set out to disprove Einstein's prediction: "I spent ten years of my life testing that 1905 equation of Einstein's and, *contrary to all my expectations*, I was compelled in 1915 to assert its unambiguous verification in spite of its unreasonableness since it seemed to violate everything we knew about the interference of light."[18]This shows that contrary

[17] Einstein (1905a), p. 146.

[18] Millikan in his autobiography (Millikan 1960, pp. 102 f.); the next quote comes from Millikan (1916), p. 18; cf. also Holton (2000) as well as Stuewer (1998) and here fn. 30.

to the claims of certain sociologists of science, experimenters do *not* always confirm what they anticipate. Even after publishing his findings in 1916, Millikan continued to have qualms about Einstein's light quantum, this "bold, not to say reckless hypothesis" (see below).

4.1 Quantization

Now we come to quantization, the 7th layer of meaning. For Max Planck, energy quantization only served as an emergency solution, introduced to prevent the interaction between radiation and resonator from leading to a growing predominance in the radiation field of oscillations of ever diminishing magnitude.[19] Planck conceived the energy of electromagnetic radiation as *continuous* because Maxwellian electrodynamics is a continuum theory.[20] According to Planck, discontinuity is only at play during the process of energy transmission from the radiation field to the oscillator. It was a quick fix to try to combine new with old.

As several physicists, including S. N. Bose (who was the first one to find a consistent remedy to this problem in 1924) pointed out, Planck's derivation from 1900 was internally inconsistent: His assumption for the energy density u of the field as a function of frequency used the following relation from classical electrodynamics:

$$u_\nu = \frac{8\pi\nu^2}{c^3} \times U \; , \tag{1}$$

that is, the resonator's absorption and emission of energy was assumed to be *continuous*. Taking Boltzmann (1877) as his model, Planck's combinatoric calculation of the 'complexions' K, that is the number of micro-states corresponding to a given macro-state of defined energy and temperature, was

$$K = \frac{(N+P-1)!}{N!P!} \; . \tag{2}$$

This step assumes the absorption and emission of energy by the resonator as *discontinuous*. In order to be able to calculate this complexion combinatorically at all, the portions of energy to be distributed among the resonators necessarily had to be assumed as finite. But Planck deemed it "just a formal assumption" even though the later boundary limit $h \to 0$ remained impossible, contrary to Boltzmann (1877).

This is where Einstein found fault. In a frequently quoted letter to Conrad Habicht from May 1905, Einstein announced a "very revolutionary" paper.[21]

[19] See M. Planck to W. Wood, 7 Oct. 1931, quoted in Hermann (1969), pp. 31 f.; cf. Needell (1980); Darrigol (1992), pp. 22–77; Gearhart (2002) for three very different account's of Planck's argumentation.

[20] See Planck's interpretation of $E = h\nu$ in letters to Lorentz on 1st of April 1908 and to Einstein on 6 July 1907.

[21] Klein/Kox/Schulman (1993), Doc. 27.

> ”So, what are you up to, you frozen whale, you smoked, canned piece of soul, or whatever else I would like to hurl at your head, filled as I am with 70% anger and 30% pity! [...]. I promise you four papers, the first of which I might send you soon, since I will soon get the complimentary reprints. The paper deals with radiation and the energy properties of light and is very revolutionary.”

What specifically was ”very revolutionary” about this paper of March 1905? *Primarily*: the introduction of light quanta. Quantization was explicitly *not* limited to resonators or the interaction between matter and the field, but also required of the energy of the electromagnetic field itself:[22]

> ”the energy of a propagating ray of light emitted from one point [is] not continuously distributed over an augmenting space but is composed of a finite number of energy quanta localized in points in space, which move without dividing and can only be absorbed and generated as a whole.”

A terminological and conceptual broadening of the word soon followed: ’light energy quanta’ (partitioning into packets of energy) became ’light quanta’ (light as a particle-like phenomenon). Just as with Planck’s energy quantization in 1900 and later with the so-called Bose-Einstein statistics in 1924/25, here also we see a *gradual* realization of the radical implications of this step. While in 1905, Einstein’s emphasis lay on energy considerations, the full-blown particle conception shines through in statements such as in Einstein’s letter to Sommerfeld, Sept. 29, 1909, where he speaks of ”the ordering of the energy of light around discrete points which move with light velocity”.[23] So by that time we have levels 1 to 7, with momentum only coming into play in his Salzburg talk of 1909, and then even more explicitly so in his paper on induced emission in 1916. It is, incidentally, normal that processes of discovery extend over months, if not years. Incidentally, this explains the problems of historians of science with jubilees of all sorts, assigning specific points in time to a given discovery or idea, as if this were a sharply delimited event.
But why was this idea of light quanta so ’revolutionary’? As we have just seen, the idea of the corpuscularity of light was very old. The novelty was the quantization of the energy of such particles. It simply could not be brought into conformance with classical continuum mechanics and Maxwellian electrodynamics. As he wrote in a confidential letter to Lorentz, Einstein realized that ”not just molecular mechanics but also Maxwell’s and Lorentz’s electrodynamics cannot be made to agree with the radiation formula.”[24]Even though Einstein was aware of this, he was very careful *not* to explicitly mention these far-reaching consequences

[22] Thus his definition of light quanta in Einstein (1905a), p. 133: compare, e.g., Pais (1982), pp. 376 ff.
[23] Klein/Kox/Schulman (1993), Doc. 179; cf. also Pais (1982), pp. 406-410 on ’the completion of the particle picture’.
[24] Thus Einstein four years later to H. A. Lorentz (30 March 1909, Klein/Kox/Schulman 1993, Doc. 146).

in his publications. The title of the 1905-paper was completely unspectacular: "On a Heuristic Point of View Concerning the Production and Transformation of Light" is dated Berne, 17 March 1905 and appeared in the issue of the *Annalen der Physik* dated 9 June 1905. At that time this journal was under the editorship of Willy Wien and Max Planck, precisely those two theoretical physicists whose work Einstein was directly extending. The term "heuristic" was even then, as it perhaps still is today, a somewhat obtuse word. Its definition spans from "problem-solving" or "tentative" to "unverifiable" or "uncertain". *Webster's Dictionary* defines "heuristic" as "providing aid and direction in the solution of a problem but otherwise unjustified or incapable of justification." Taken together with the statement in his letter to Habicht, it is clear that Einstein knew that his postulate was bold, and that caution was necessary. Therefore the conjunctive in Einstein's formulation from March 1905.

He certainly does *not* say: light quanta of energy $E = h\nu$ *do exist*. His choice of words is much more careful. He only says that monochromatic radiation of frequency ν in the Wien limit could be interpreted *as if* it were composed of distinctly separate energy quanta. The interaction between the matter and the field would then consequently be composed of the emission and subsequent absorption of such quantized packets of energy: This idea reappears in Bohr's model of the atom. Unlike Bohr's later model, however, Einstein's paper of 1905 offers no specific model of this process. Einstein's argumentation follows Gustav Robert Kirchhoff's style, Planck's teacher and the first professor of theoretical physics at the University of Berlin: there are *no* models for matter, only the most general assumptions possible independent of any models. Likewise Planck's 'resonators' - *not* concrete atoms or molecules, but generally oscillatory systems; likewise Kirchhoff's 'black body.' Both are examples of this conceptualizing style to which Einstein adapted his *Annalen* papers.

But how did Einstein argue for the existence of light quanta of energy or at least their plausibility? He resorted to his typical strategy of following two separate derivations at the same time. He thus analysed a single system according to two different theoretical methods as far as he could. His second step sought to equate the physical expressions obtained by along two different paths.

Let there be n of these light quanta (or more generally, particle-like localized systems) in a volume V_0. We then ask how probable it is that all these n point-like systems lie not just in the initial volume V_0 but also within a smaller area V within it. The smaller V is against V_0, the less probable it is. The solution to this problem can be calculated by means of general probability theory as well as from Wien's and Planck's radiation theory. Since both are supposed to be compatible, both expressions ought to be equatable. This is only possible if $E = h\nu$ is true. q.e.d.

Einstein's 1905 juxtapositioning of an ideal gas according to Boltzmann statistics with radiation in the Wien limit thus led to the light quantum hypothesis: "monochromatic radiation of low density [at the Wien limit] acts *as if*

it were composed of mutually independent quanta of energy of the magnitude $(R\beta\nu)/N \times \nu\,[= h \times \nu]$".[25]
As is typical for Einstein's thinking, the originality of this consideration lay in a new way to link different chains of reasoning; here classical combinatorics with statistical mechanics à la Boltzmann and Gibbs and radiation theory à la Wien and Planck. This derivation also reveals another characteristic of Einstein's thinking: the constant back and forth between micro- and macro-physics as encapsulated in the formula $S = k\ln W$ which Einstein termed Boltzmann-formula and used to full extent in both directions. This also applies to Einstein's papers on fluctuation phenomena [Brownian motion (1905) and the induced observable oscillatory effects of a mirror (1909)].
Einstein's correspondence with Lorentz and his Salzburg lecture of 1909 show that he certainly had a quite fully developed model of light quanta, quite comparable to the one depicted in Newton's sketch at the beginning of this paper.[26]

> "For the time being the most natural interpretation seems to me to be that the occurrence of electromagnetic fields of light is associated with singular points just like the occurrence of electrostatic fields according to the electron theory. It is not out of the question that in such a theory the entire energy of the electromagnetic field might be viewed as localized in these singularities, exactly like in the old theory of action at a distance. I more or less imagine each such singular point as being surrounded by a field of force which has essentially the character of a plane wave and whose amplitude decreases with the distance from the singular point."[27]

Einstein's shyness in explicitly discussing this conceptual model is due to three profound problems which he encountered in its development:

1. Problems with explaining **interference** (letter by H.A. Lorentz, 6 May 1909) $\rightarrow$ strong deviations from point-like structure?

2. Problems with interpreting **partial reflection**: the splitting of photons is impossible!

3. Problems with **particle characteristics** of light quanta: if they transmit energy, then they do have mass according to $E = mc^2$, but no massive particle can have the velocity of light.

While the solution to the third enigma, of course, was to assume vanishing rest mass of the photon, the other two problems proved to be much harder as they were intimately linked with the horny issue of wave-particle duality.[28]

[25] Einstein (1905a), p. 143, reprint in Cassidy et al. (1990), p. 161; cf. furthermore Dorling (1971) and Stachel (2002).
[26] Einstein (1909c), Cassidy et al. (1990), pp. 224 f., Einstein/Ritz (1909), pp. 323 f. as well as Einstein (1909b).
[27] Einstein (1909a), p. 499, Cassidy et al. (1990), p. 581, engl. translation p. 394.
[28] See, e.g. Bach (1989); Irons (2004) and Klein (1964).

Einstein's letters leave traces of this reserve. In an intensive exchange of letters about the light quantum hypothesis since the beginning of 1909 with Hendrik Antoon Lorentz in Leyden, Einstein wrote on 23 May 1909: "You can hardly imagine how much I look forward to making your personal acquaintance [...]. From the outset let me aver that I am not the orthodox light-quantum-man [*Lichtquantler*] that you hold me for. That may have come from the vague form of expression in my papers." A letter to his close friend Michele Besso dated 13 May 1911 reveals that this was more than mere politeness: "I don't ask myself anymore whether these quanta really exist. I don't try to construct them anymore either, because I now know that my brain cannot come through that way. But I am systematically examining the consequences carefully in order to find out about the area of applicability of the idea." He also wrote to his mathematician friend Ludwig Hopf at the end of February 1912: "The quanta do what they are supposed to, but they don't exist, like the light aether at rest. The latter is turning busily in its grave with the intention of coming back to life - the poor thing."[29] Einstein had given up hope of finding a theory of light quanta along a constructive path, such as Lorentz had done with his electron theory of metals. It did not suffice either for a pseudo-axiomatic theory of principle, of the type of his theory of relativity. The only alternative was this third route, a constant skipping back and forth between micro and macro-physics. This, as already mentioned, was Einstein's most successful strategy.

5 Reception of the light quantum

Strangely enough, one of the first advocates of the light quantum hypothesis was Johannes Stark. His arguments were foremost experimentally based:[30]

1. Photoelectric effect
2. Shortwave limit of X-ray *bremsstrahlung*
3. Intensity minimum of the Doppler effect
4. (generally:) Discrete excitation energy of atoms
5. (personally:) His tendency to go against generally accepted opinions

But Stark had to swallow criticism for his support of the light quantum: In February 1911 Hantaro Nagaoka wrote to Ernest Rutherford:[31]

> "Stark [... in Aachen] was propounding his 'Lichtquantentheorie'; there is some doubt whether he will succeed in explaining the interference phenomena, or not. The Germans say that he is full of phantasies, which may be partly true."

[29] On the preceding quotes see Klein/Kox/Schulman (1993), Doc. 163, p. 193, Doc. 267, p. 295 and Doc. 364, p. 419.

[30] On Stark's arguments see esp. Wheaton (1983) and Pais (1982), p. 409 on the momentum balance for Bremsstrahlung.

[31] Quoted after Badash (1967), p. 59.

Arnold Sommerfeld and many others remained skeptical. On 10 Oct. 1908, Sommerfeld wrote a letter to Stark with a request for a spectrogram:

> ”[... the] quantum exposure, which I would like to use for teaching, but above all to convert myself definitively to Planck’s fundamental hypothesis.”

This document shows that Sommerfeld at that time still had strong doubts about energy quantization. In a letter dated 4 Dec. 1909 Sommerfeld reflected on: ”the really very hypothetical and uncertain light quantum theory [...] Not as if I were doubting the significance of the quantum of action. But the form in which you present it (light quantum) appears, not just to me but also to Planck, very daring.” Max Planck was similarly skeptical. In the *Annalen der Physik* of January 1910 he wrote: ”I cannot at the moment acknowledge compelling proof in favor of the corpuscular theory of light any more for J. Stark’s experiments on X-rays than for A. Einstein’s deductions.”
The great majority of physicists at that time were even more adverse to it, particularly Max Planck. He saw ”no compelling reason” for abandoning Maxwell’s equations along with its continuum physics. His skepticism of the light quantum hypothesis was shared by many others. It also took Robert Millikan, for instance, many years to befriend himself with it. He was still aloof towards it in his Nobel lecture of 1924.[32]

> ”After ten years of testing and changing and learning and sometimes blundering [...] this work resulted, contrary to my own expectation, in the first direct experimental proof [...] of the exact validity [...] of the Einstein equation and the first direct photo-electric determination of Planck’s h. [...] The general validity of Einstein’s equation is, I think now universally concluded, 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.”

He only made his peace with the light quantum in 1950 when he wrote: [33]

> The experimental data ”proved simply and irrefutably, I thought, that the emitted electron that escapes with the energy hv gets that energy by the direct transfer of $h\nu$ units of energy from the light to the electron and hence scarcely permits any other interpretation than that which Einstein had originally suggested, namely that of the semi-corpuscular or photon theory of light itself.”

Notice how Millikan slyly implies with the insertion “I thought” that this conclusion had been the one he made from the start, whereas we have just seen that it had taken him several decades to reconcile himself with Einstein’s ”bold, not to say reckless hypothesis” of light quanta.

[32] Millikan (1965), pp. 61 ff.
[33] Millikan (1960), p. 101 f. Cf. Stuewer (1998) and Holton (2000) pointing out Millikan’s tendency to silently suppress his former critical stance on this issue of light quanta.

6 Conclusion

Let us review now, at the end of my talk, the many layers of meaning of the mental model of the 'light quantum' (now called the photon):

localized (particle-like)	Newton's projectile model 1687/1704
propagation at finite velocity of light	Roemer, Huygens, Newton
equality of the velocity of light for all colors/frequencies	Newton (initial doubts)
light transmits energy E	Maxwell, Poynting, Einstein 1917
light transmits momentum $p = E/c$ (radiant pressure)	Newtonian: Homberg 1708; Mairan 1747,... exp.: Lebedev 1901, Nichols & Hull 1903 f., Stark 1909, Compton 1923,...; theor.: Einstein 1909, 1916
energy E of light is correlated with its frequency: $E \sim \nu$	Einstein 1905 (Erich Ladenburg still thinks in 1907 that the proportionality constant varies with the emitting material!)
energy E of light quanta is quantized: $E = h\nu$ (with h the same universal constant for all materials)	Einstein 1905
in the limit of short wavelengths light quanta appear particle-like, in the limit of long wavelengths, they are wave-like (wave-particle duality)	Einstein 1909 ... Bohr 1927
emission and absorption by matter in whole quanta	Einstein 1915 (photochem. equiv. law: Stark 1908, Einstein 1912)
light quanta transmit angular momentum: spin is ± 1	(Sommerfeld, Landé), Goudsmit & Uhlenbeck for electrons 1925, Dirac 1926
any two light quanta of the same E and spin orientation are indistinguishable	
statistics of these light quanta ('Bose-Einstein statistics')	(Planck), Natanson 1911, Bose, Einstein 1924/25

We see that some of these layers are very old. Others only became evident after Einstein's paper of 1905. *On the whole* the modern concept of photons actually only dates back to the end of 1925. So it is no coincidence that the modern term 'photon' was introduced so late (in 1926 by Gilbert Lewis).[34]Our summarizing list shows that other people had already recognized many of these layers, on their own, to varying degrees of precision. But this does not reduce the importance of

[34] Lewis (1926).

Einstein's contributions to knowledge about the strict quantization of energy in a field of radiation (layer no. 7: 1905) and later on wave-particle duality (1909: layer 9). Einstein's Salzburg talk was the first step towards the wave-particle duality, later further expanded by Louis and Maurice de Broglie, Bohr and others.
Layers 6 to 8 were extremely bold steps to which others had neither the courage nor the far-reaching intellectual perspicuity. But as with his theory of relativity, Einstein's most important achievement was drawing together all these individual insights into a first intrinsically consistent quantum theory of radiation. Einstein's 'On a Heuristic Point of View Concerning the Production and Transformation of Light' of March 1905 merged combinatoric techniques by Boltzmann with ideas by J.J. Thomson, Wien, Planck and Lorentz together with the experimental findings of Stokes, Lenard and others into a single organic whole. That was why it was necessary to shed certain elements of this conceptual legacy, such as Planck's doubts about any justification for a quantization of the radiation field itself or Lorentz's problems with an explanation for interference. Einstein's greatest strength lay in *tracking down* heuristically fruitful strands of ideas from the large reservoir of conceivable options at the time, in consistently shedding elements that did not agree and weaving these previously separate strands into theories that are not just consistent but also empirically adequate.

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