International Year of Light Blog

Einstein 1905: From "Energy quanta" to "Light quanta"

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"The energy of a light ray spreading out from a point source is not continuously distributed over an increasing space [wave theory of light] but consists of a finite number of energy quanta which are localized at points in space, which move without dividing, and which can only be produced and absorbed as complete units." With these words Albert Einstein (https://en.wikipedia.org/wiki/Albert_Einstein) (1879-1955) introduced his *"heuristic point of view toward the emission and transformation of light"* which was presented in his first *Annus Mirabilis* paper published in 1905, a year that Einstein himself referred to as "very revolutionary". Einstein introduced the concept of "light quanta", an indivisible packet, although it was not until 1926 when the term "photon" (coined by Gilbert Lewis (https://en.wikipedia.org/wiki/Gilbert_N._Lewis) (1875-1946) in an article published in *Nature*) substituted Einstein's "light quanta" forever.

Of course, this year 2015 marks the centenary of the publication of Einstein's papers on general relativity and –as the IYL 2015 Resolution points out– "the embedding of light in cosmology thorough general relativity". However, perhaps it is not so well known that Einstein also made several seminal contributions to the science of light. He did not only introduce in 1905 the concept of "light quanta" and applied it to theoretically study "the emission and transformation of light", as it has been mentioned before, but he also postulated stimulated emission in 1916, which eventually became the basis of laser operation. Besides these two contributions, Einstein was also one of the pioneers in exploring the wave-particle duality of light in a paper published in 1909. There is no doubt that Einstein gave us a remarkable legacy in light.

Albert Einstein in 1905. Credit: Wikipedia.

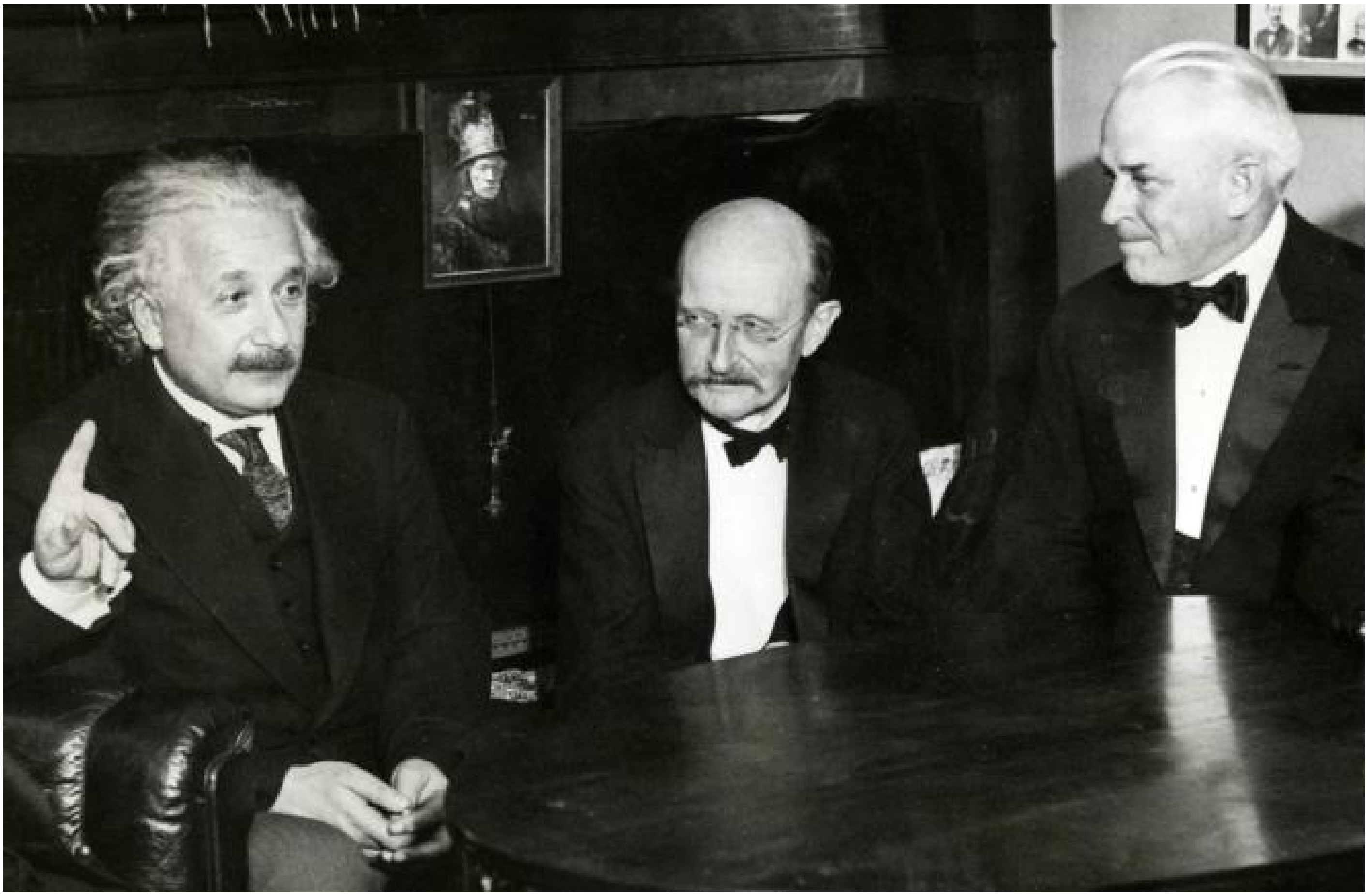
Of all great scientific achievements made by Einstein –according to Time magazine, the “Person of the Twentieth Century”, the genius among geniuses–, I chose for this contribution one of them and my election was based on three reasons. First, because it was Einstein who convincingly introduced the idea of “light quanta” (later renamed “photon”). The second, because Einstein was the first scientific that applied Planck’s ideas, before any of his colleagues, to explain theoretically another physical phenomenon in 1905. And the third, because the United Nations resolution in which 2015 was declared as International Year of Light refers to this important milestone in the history of science of light. The reader will have guessed by now that we are referring to the photoelectric effect (http://light2015blog.org/2015/06/23/light-knocks-physics-for-a-leap-the-photo-electric-effect/).

En 1887, Heinrich Hertz (https://en.wikipedia.org/wiki/Heinrich_Hertz) (1857-1894) discovered the photoelectric effect (https://en.wikipedia.org/wiki/Photoelectric_effect). It is the observation that many metals emit electrons when light shines upon them. These electrons are known as photoelectrons. Do not think that this effect is something that can only be found in research laboratories. As Doris Kimbrough reminds us “the photoelectric effect is used in many modern conveniences, such as your supermarket’s automatic door openers, motion detectors, and night vision googles, an its applications extend to solar-powered calculators and your friend, the television”. The physicist Phillip Lenard (https://en.wikipedia.org/wiki/Philipp_Lenard) (1862-1947) demonstrated in 1902 that if radiation of sufficiently short wavelength is incident on a metal’s surface, then electrons are emitted (ultraviolet light facilitates the process). There were several conclusions derived from experiments. For example, for each type of material there is a specific frequency of radiation (its "colour") below which no electrons are emitted, or that the maximum kinetic energy of the emitted photoelectrons is independent of the intensity of the incident light. Unfortunately, these experimental facts could not be explained using the Maxwell's electromagnetic theory of light (other of the milestones commemorated in this International Year of Light). According to Maxwell's theory, for a weak incident light, a delay would have to appear between the instant in which light begins to impinge on the metal surface and the instant in which photoelectrons are emitted. However, this delay has never been measured.

In 1900 Max Planck (https://en.wikipedia.org/wiki/Max_Planck) (1858-1947) was the first to correctly give a theoretical interpretation for the electromagnetic radiation emitted by a black body in thermal equilibrium at a definite temperature. Using thermodynamics arguments and an *ad hoc* hypothesis, he found an equation which fitted the experimental data quite well. After six years working on this issue, and in an "act of desperation" (as Planck himself called his *ad hoc* hypothesis), he considered that the total energy of the blackbody resonators was made up of small *indivisible* "elements", each one of magnitude E, and he assumed that the energy E of each of these "elements" was proportional to the frequency f with which the resonators vibrated, $E = hf$, being h a proportionality constant (which is now known as Planck's constant). The first quantum discontinuity was born. However, Planck was cautious in the use of his quantum concept because he was conservative in nature. For him, after radiation, the electromagnetic energy spreads in space as electromagnetic waves.

On March 17, 1905, three days after his twenty-sixth birthday, a young Einstein sent a paper from the city of Bern to the *Annalen der Physik*, the leading German physics journal, entitled "On a heuristic point of view concerning the generation and conversion of light." In this paper, he presented in a "heuristic point of view" that real quanta existed and that they can be found in certain experiments as constituents of light and other type of radiations. The second quantum discontinuity was born and, with it, the "light quanta". Einstein made some of his greatest scientific achievements between 1902 and 1909, when that unknown giant occupied a humble position as "technical officer" at the Swiss Federal Patent Office in Bern. His bread-winning job left him enough time for developing an extraordinary scientific work, one after another. In fact, Einstein himself called these years in Bern not only the happiest but also the most fruitful period in his life. Einstein was one of the few physicists attracted to Planck's early quantum theory, and probably one of the few who had glimpsed its applicability to other physical phenomena. In fact, by the year 1905, Planck's ideas were not well known. Suffice it to mention, for example, that in 1911, at the first Solvay Conference (https://en.wikipedia.org/wiki/Solvay_Conference) Einstein himself stated "I insist on the provisional character of this concept [light quanta]" and they were not applied to the description of the atom until Niels Bohr did in 1913. There is no doubt that the work of Einstein on "light quanta" published in 1905 was responsible for this application.

In his 1905 paper, Einstein used his "light quantum hypothesis" to explain the photoelectric effect, which is analysed in a brief section of this paper entitled "on the generation of cathode rays by illumination of solid bodies". Light consists of energy quanta, each of amount hf, the quanta penetrate the surface layer of metal. A light quantum transfers its energy to a single electron and part of this energy is transformed into kinetic energy of the electron and the other part, W, is used to remove it from the metal (W is the energy the electron loses on leaving the metal). W is a function of each material and it is called the "work function". Taking this into account, the maximum kinetic energy of an ejected electron is $hf - W$. One hundred years after Thomas Young convincingly demonstrated the wave nature of light through the double-slit experiment, Einstein presented to the scientific community what appeared to return to the ideas once proposed by Newton that light was composed of a stream of particles. The immediate response of this community to his new concept of “light quanta” did not seem to be very great: “Particles of light? It is a terrible idea!” Planck himself was one of those who were more critical of the idea of “light quanta”, and Robert Millikan (https://en.wikipedia.org/wiki/Robert_Andrews_Millikan) (1868-1953) called the idea of Einstein as reckless.



From left to right: Einstein, Planck and Millikan in 1931. Credit: Wikipedia.

Finally, in 1916 and after ten years of experiments, it was Millikan himself who did not only validate Einstein’s equation for the photoelectric effect but he also “photoelectrically” determined Planck’s constant, *h*, with a great precision. Millikan’s paper ends with a conclusion that leaves no room for doubt: “Einstein’s photoelectric equation has been subjected to very searching tests and it appears in every case to predict exactly the observed results.” However, at the beginning, Millikan tried to demonstrate that Einstein’s ideas about “light quanta” were wrong. In a paper published in 1949 on the occasion of Einstein’s seventieth birthday, Millikan wrote: “I spent ten years of my life testing that 1905 equation of Einstein’s [the equation of the photoelectric effect], and, contrary to all my expectations I was compelled in 1915 to assert its unambiguous experimental verification in spite of its unreasonableness since it seemed to violate everything that we knew about the interference of light.”

But the story about the photoelectric effect ended happily for both Einstein to and Millikan. Both were awarded with the Nobel Prize in Physics, Albert Einstein in 1921 “for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect” (http://www.nobelprize.org/nobel_prizes/physics/laureates/1921/), and Robert Millikan in 1923 “for his work on the elementary charge of electricity and on the photoelectric effect” (http://www.nobelprize.org/nobel_prizes/physics/laureates/1923/). To this we must add that in 1905 Phillip Lenard also received the Nobel Prize in Physics “for his work on cathode rays” (http://www.nobelprize.org/nobel_prizes/physics/laureates/1905/) and part of “his work” included his research on the photoelectric effect. Surely no one would have thought that something as the photoelectric effect would have produced so many Nobel Prize winners.

More Information

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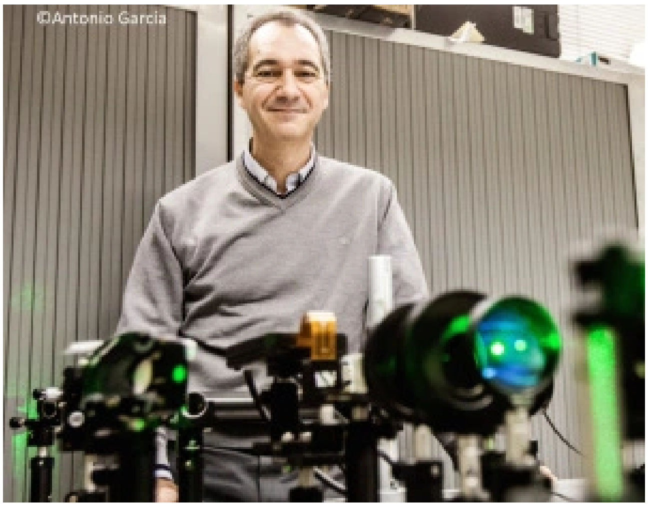

He is active in public outreach: he has published numerous articles in popular science journals, and in the media. In 2009 he started the blog “Física para tod@s”, and he has given some talks to general public on science.

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