The Story of the Photon

N Mukunda

An account of the story of the light quantum or photon is given, from its inception in 1905 to its final acceptance in 1924. Necessary background information on radiation theory and historical details are included.

N Mukunda is at the Centre for Theoretical Studies and the Department of Physics of the Indian Institute of Science, Bangalore. His research interests are in classical and quantum dynamical formalisms, theoretical optics, and general mathematical physics. In addition he writes occasionally on conceptual and historical aspects of science for general audiences.

Introduction

The photon, so named by the physical chemist Gilbert Norton Lewis in 1926, is a child of the 20th century. It is the 'particle of light' – or 'light quantum' – first hypothesized by Albert Einstein in 1905, and then used by him to explain, among other things, the photoelectric effect. The story of the photon is rich in history, development of ideas, experiment and personalities. In this account an attempt will be made to convey something of each of these aspects; the fundamental motivations and currents of ideas will be described as carefully as possible, and only selected derivations will be presented.

During the year 1905, aptly called 'Einstein's Miraculous Year', he submitted five research papers for publication and also completed his Ph.D. thesis. Of the former, three have become all-time classics. In chronological sequence they are: the light quantum paper (March), the paper on the Brownian Motion (May), and the paper establishing the Special Theory of Relativity (June). Einstein himself felt that of these only the first was truly path-breaking, for he wrote in a letter of May 1905 to his friend Conrad Habicht: "I promise you four papers ...... the first of which I could send you soon.... The paper deals with radiation and the energetic properties of light and is very revolutionary, as you will see. ....".

Radiation Theory from Kirchoff to Planck – a Capsule

The study of (electromagnetic) radiation forms a glorious chapter in the history of physics. The first major step was

 Appeared in Vol.5, No.3, pp.35-51, 2000

"I promise you four papers ... the first of which I could send you soon, since I will soon receive the free reprints. The paper deals with radiation and the energetic properties of light and is very revolutionary, as you will see...."

Einstein to Conrad Habicht, May 1905

taken in 1859 by Gustav Kirchoff (the 'grandfather' of the quantum theory) when he proved the following result: if radiation and material bodies are in equilibrium at a common (absolute) temperature T, the former being reflected, scattered, absorbed and emitted by the latter, then the energy density of the radiation per unit frequency interval is a *universal* function of frequency and temperature, independent of the particular material bodies present:

$$\begin{aligned}\rho(\nu,T)\Delta\nu &= \text{energy of radiation per unit volume} \\ &\quad \text{in the frequency range} \\ &\quad \nu \text{ to } \nu+\Delta\nu, \text{ at temperature } T \\ &= (\text{universal function of } \nu \text{ and } T) \times \Delta\nu. \quad (1)\end{aligned}$$

For the proof, Kirchoff used the Second Law of the then young science of thermodynamics; and he posed the determination and understanding of the function $\rho(\nu,T)$ as a major experimental and theoretical challenge. Such radiation is variously called 'black-body' or 'temperature' or 'thermal' radiation.

Twenty years later, in 1879, the experimentalist Josef Stefan measured the total energy density of thermal radiation by 'summing' over all frequencies, and then conjectured that it was proportional to T^4:

$$\begin{aligned}u(T) &= \text{total energy density of thermal radiation} \\ &= \int_0^\infty d\nu\, \rho(\nu,T) = \sigma\, T^4 \qquad (2)\end{aligned}$$

Soon after, in 1884, Ludwig Boltzmann was able to give a thermodynamic proof of this result, using Maxwell's result that the pressure of radiation is one third of its energy density. (See *Box* 1.) Once again, this was an outstanding and early application of thermodynamics to radiation problems – more were to follow. The constant σ in (2) is named jointly after Stefan and Boltzmann.

From the 1860's onwards many guesses were made for the form of the function $\rho(\nu,T)$. In 1893 Wilhelm Wien constructed a clever thermodynamical argument and proved

Box 1. Thermodynamics and the Stefan – Boltzmann Law

Consider thermal radiation, at temperature T, enclosed in a spatial volume V, and treat T and V as independent variables. The total energy $U = V\ u(T)$ where $u(T)$ is the energy density including all frequencies. The pressure, according to Maxwell, is one third the energy density : $p = \frac{U}{3V} = \frac{u(T)}{3}$. (In contrast, for a classical (nonrelativistic) ideal gas of n particles the total energy $U = \frac{3}{2}nkT$ is volume independent; while from the ideal gas law the pressure is two-thirds the energy density, $p = \frac{2}{3}\frac{U}{V}$). The Second Law of Thermodynamics implies that the expression

$$dS = \frac{1}{T}(dU + pdV)$$

must be a perfect differential. Writing this out as

$$dS = \frac{1}{T}\left(u(T)dV + V\frac{du(T)}{dT}dT + \frac{u(T)}{3}dV\right),$$

this means that

$$\frac{\partial}{\partial T}\left(\frac{4}{3}\frac{u(T)}{T}\right) = \frac{\partial}{\partial V}\left(\frac{V}{T}\frac{du(T)}{dT}\right),$$

which simplifies to

$$T\frac{du(T)}{dT} = 4\ u(T).$$

The solution is the Stefan–Boltzmann Law:

$$u(T) = \text{Constant} \times T^4$$

that the dependences of $\rho(\nu, T)$ on its two arguments were correlated by a *scaling law*:

$$\rho(\nu, T) = \nu^3 f(\nu/T), \qquad (3)$$

so the original Kirchoff problem became that of finding the form of the universal function $f(\nu/T)$ involving only one argument. He followed this up soon after in 1896 by offering a guess for the form of $f(\nu/T)$, inspired by the Maxwell velocity distribution in a classical ideal gas: with two constants α and β he suggested

$$\begin{aligned} f(\nu/T) &= \alpha\, e^{-\beta\nu/T}, \\ \rho(\nu,T) &= \alpha\, \nu^3\, e^{-\beta\nu/T} \end{aligned} \tag{4}$$

Early experiments by Friedrich Paschen (reported in January 1897) gave support to the Wien Law (4). They were done in the near infrared part of the spectrum, with wavelengths λ in the range (1 to 8)$\times 10^4$ $\mathring{A}$ and temperatures T in the range 400 to 1600 K; and showed the validity of the Wien Law in the high frequency limit.

Now we turn to Max Karl Ernst Ludwig Planck, successor to Kirchoff and the 'father' of the quantum theory. His major goal was the theoretical determination of Kirchoff's universal function $\rho(\nu,T)$. For a while he believed that the Wien Law (4) was correct for all ν and was the answer to Kirchoff's problem; his task was to find a proper theoretical basis for that law. In the 1890's he carried out many fundamental investigations on the interaction of Maxwell's electromagnetic waves with matter; he was a master of thermodynamics as well. However during 1900 new experiments showed deviations from the Wien Law (4) in the low frequency limit, and there were new theoretical developments as well. In February 1900 the experiments of Otto Lummer and Ernst Pringsheim in the far infrared region $\lambda = (1.2$ to $1.8) \times 10^5 \mathring{A}$ and $T = 300$ to 1650 K showed disagreement with the Wien Law (4). In June 1900 Lord Rayleigh applied the equipartition theorem of classical statistical mechanics to thermal radiation treated as a system on its own and derived the result

$$\begin{aligned} f(\nu/T) &= c_1\, T/\nu, \\ \rho(\nu,T) &= c_1\, \nu^2 T,\ c_1 \text{ a constant.} \end{aligned} \tag{5}$$

(After further work by Rayleigh in May 1905 calculating c_1 and a later correction by James Hopwood Jeans in June-July

1905, this Rayleigh–Jeans Law attained its final exact form

$$\begin{aligned} f(\nu/T) &= \frac{8\pi k}{c^3}\,\frac{T}{\nu} \\ \rho(\nu,T) &= \frac{8\pi\nu^2}{c^3}\cdot k\,T, \end{aligned} \tag{6}$$

with c the vacuum speed of light and k the Boltzmann constant). Slightly later, by October 1900, Heinrich Rubens and Ferdinand Kurlbaum did experiments in the deep infrared, $\lambda = (3 \text{ to } 6) \times 10^5\ \mathring{A}, T = 200 \text{ to } 1500K$, and found again deviations from the Wien Law (4) but agreement with the Rayleigh expression(5).

Sunday, October 7, 1900 is the birthdate of the quantum theory. On the afternoon of that day, Rubens visited Planck's home for tea, and told him of his and Kurlbaum's latest experimental results. After he left, Planck set to work. He realised that Wien's Law could not be the final answer to Kirchoff's problem. While it was obeyed at high enough frequencies, it failed at the low frequency end where the Rayleigh form was valid. What Planck achieved that evening was a mathematical interpolation between these two limiting forms. His strategy seems roundabout but was, in retrospect, fortunate. He had in earlier work related the Kirchoff function $\rho(\nu,T)$ to the average energy $\overline{E}(\nu,T)$ of a charged material oscillator with natural frequency ν and at a temperature T, by balancing the effect on it of incident radiation and its own emission of radiation. This 'Planck link' reads

$$\rho(\nu,T) = \frac{8\pi\nu^2}{c^3}\,\overline{E}(\nu,T). \tag{7}$$

Planck translated the limiting forms of $\rho(\nu,T)$ in the high ν(Wien) and low ν (Rayleigh) limits into corresponding limiting forms for $\overline{E}(\nu,T)$; converted this into limiting forms for the entropy $S(\overline{E})$ of the material oscillator (written as a function of energy) at high and low $\overline{E}$, respectively; and then by solving a simple differential equation found a formula interpolating between these limiting expressions. Translating all this back into the original problem his result for Kirchoff's function $\rho(\nu,T)$ is the Planck radiation law we all know so well:

$$\rho(\nu,T) = \frac{8\pi\nu^2}{c^3} \; \frac{h\nu}{e^{h\nu/kT}-1} \tag{8}$$

A new fundamental constant of nature with the dimensions of action, Planck's constant h, entered his result; and there was agreement with experiment at all measured frequencies. On October 19, 1900, Planck announced his formula following a talk given by Kurlbaum. In the high frequency limit we recover the Wien result (4) from (8) with

$$\alpha = 8\pi h/c^3, \; \beta = h/k \tag{9}$$

Comparing (7) and (8) it follows that Planck's formula implies that the average energy of a material oscillator $\overline{E}(\nu,T)$ must have a value differing from the result kT of the equipartition theorem:

$$\overline{E}(\nu,T) = h\nu/\left(e^{h\nu/kT}-1\right) \tag{10}$$

During the period October to December 1900 Planck tried very hard to find a theoretical basis for this formula. Finally, "...as an act of desperation.... to obtain a positive result, under any circumstances and at whatever cost", he invented the concept of irreducible packets or quanta of energy for matter, and in mid-December 1900 he presented the following statistical derivation of (10). He imagined a large number, N, of identical (but distinguishable!) material oscillators, with a total energy E and at a temperature T. Assuming that this total energy E was made up of P (indistinguishable!) packets or quanta of energy ϵ_0 each, (so that $E = P\epsilon_0$ and the energy of each oscillator is an integer multiple of ϵ_0), he counted the number of ways W (number of micro states or complexions) in which these packets could be distributed over the N oscillators. By a simple combinatorial argument, followed by an application of the Boltzmann entropy relation $S = k \ln W$, he computed the entropy S/N per material oscillator, connected it up to the temperature T, and finally arrived at the result (10) he was after, with the identification $\epsilon_0 = h\nu$.[1]

[1] The symbol k for Boltzmann's constant first appeared in the Planck Law (8) in 1900. The formula $S=k\ln W$ was given the name 'Boltzmann's Principle' by Einstein.

Einstein's State of Preparedness

It is time now to turn to Einstein. Already since 1897 during his student days at the Eidgenossische Technische Hochschule in Zurich he had become familiar with Kirchoff's work on thermal radiation. From his teacher Heinrich Friedrich Weber in 1899 he learnt about Wien's theorem (3) and the resulting Wien Displacement Law. He was also familiar with Planck's work, and while he had full faith in the experimental validity of the Planck law (8), he was acutely conscious of the absence of a proper theoretical basis for it. (See *Box* 2 for a brief account of Einstein's involvement with Planck's Law). During the period 1902–1904 he rediscovered for himself the foundations and key concepts of statistical physics, obtaining independently many of Josiah Willard Gibbs' results. He invented on his own the concept of the canonical ensemble, derived the equipartition law for energy, found ways to use the 'Boltzmann Principle' $S = k \ln W$, and found the formula for energy fluctuations

Box 2. Einstein and the Planck Law

Here is a chronological list of the many occasions and ways in which Einstein 'played' with the Planck radiation law and 'teased out' its deep consequences:

1905: Examines the volume dependence of entropy of radiation in the Wien limit, abstracts the light quantum idea, applies it inter alia to the photoelectric effect.

1909: Calculates energy fluctuations for thermal radiation using the complete Planck Law; arrives at the earliest ever statement of wave-particle duality in nature; considers also momentum fluctuations of a mirror placed in thermal radiation, due to fluctuations in radiation pressure.

1916: Derives the Planck Law based on Bohr's theory of stationary states and transitions, and processes of absorption, induced and spontaneous emission of radiation by matter. Extends the 1905 analysis to show that individual light quanta are directed in space and carry momentum.

1924-25: Extends Bose's derivation of the Planck Law to matter, finds particle-wave duality for matter, predicts Bose–Einstein condensation.

for a mechanical system at a given temperature. (See later.) The empirical validity of the Planck Law (8) and the realisation that it could not be derived from the classical Maxwell theory of electromagnetic radiation convinced him that the picture of radiation given by the latter had to be modified by incorporating quantum features in some way. As he was to say much later: "Already soon after 1900, ie., shortly after Planck's trailblazing work, it became clear to me that neither mechanics nor thermodynamics could (except in limiting cases) claim exact validity".

Einstein independently derived, in his March 1905 paper, the Rayleigh–Jeans Law (6): he started from the 'Planck link' (7) between radiation and matter, used the equipartition law to substitute kT for the average energy $\overline{E}(\nu, T)$ of the material oscillator, and directly obtained (6)! Thus there were two theoretically well-founded, but experimentally invalid, routes to the Rayleigh–Jeans result: one applying equipartition directly to radiation; and another using the 'Planck link' and then applying equipartition to the material oscillator.

Added to all this, it should be mentioned that in the course of some work on the molecular theory of gases done in 1904, Einstein had realised the importance of the volume dependence of thermodynamic quantities, in particular of the entropy. The relevance of this will become clear presently.

The 'Light Quantum' Paper of 1905

Einstein's views, circa 1905, on the radiation problem may be summarised as follows: the Planck Law is experimentally accurate but has no proper theoretical basis; the Rayleigh–Jeans limit has a proper classical theoretical foundation but is experimentally unacceptable; the Wien limit is a guess, with no derivation from first principles or classical basis, and is experimentally valid only at high frequencies. He also declared right away that, in spite of the success of Maxwell's wave theory in explaining typical optical phenomena, he believed it was necessary to replace it by a different picture in which radiant energy is made up of discontinuous spatially localized quanta of finite energy, which could be absorbed and emitted only as complete units.

Einstein then took a 'phenomenological' attitude to the radiation problem: since Wien's Law (4) is experimentally valid in a definite domain and has no classical underpinnings, an examination of this domain from the thermodynamical point of view – involving radiation on its own and not using the 'Planck link' at all – should reveal key nonclassical features of radiation.

Apart from the independent derivation mentioned above of the Rayleigh-Jeans Law, in his paper Einstein recalls some results of Wien on the entropy of radiation. He then uses this to calculate the volume dependence of the entropy of thermal radiation in the Wien limit; gives the corresponding calculation for a classical ideal gas; compares the two results; and then draws his epoch-making conclusions about the existence and nature of radiation quanta. The Wien limit calculation given by Einstein is essentially equivalent to the following.

Consider thermal radiation at temperature T and between frequencies ν and $\nu + \Delta\nu$, contained in a spatial volume V. The total energy, E say, of this radiation is given, when the Wien limit is applicable, by

$$\begin{aligned} E &= V\,\alpha\,\nu^3\,e^{-\beta\nu/T}\;\;\Delta\nu = \mathcal{N}\,V\,e^{-\beta\nu/T} \\ \mathcal{N} &= \alpha\,\nu^3\,\Delta\,\nu. \end{aligned} \tag{11}$$

Treating E and V as the independent thermodynamic variables, the inverse temperature is

$$\frac{1}{T} = \frac{1}{\beta\nu}(\ln\mathcal{N} + \ln V - \ln E). \tag{12}$$

The entropy $S(E,V)$ of this portion of Wien radiation is obtained by integrating the basic thermodynamic relation

$$\frac{\partial S(E,V)}{\partial E} = \frac{1}{T} = \frac{1}{\beta\nu}(\ln\mathcal{N} + \ln V - \ln E), \tag{13}$$

the dependences of $S(E,V)$ on ν and $\Delta\nu$ being left implicit.

This leads to

$$S(E,V) = \frac{E}{\beta\nu}(\ln \mathcal{N} + \ln V + 1 - \ln E), \qquad (14)$$

(apart from a function of V alone which must vanish since $S(E,V) \to 0$ as $E \to 0$). If we now compare the values of the entropy for two different volumes V_1 and V_2, keeping E (and of course ν and $\Delta\nu$) fixed, we find:

$$\begin{aligned} S(E,V_1) - S(E,V_2) &= \frac{E}{\beta\nu} \ln\left(\frac{V_1}{V_2}\right) \\ &= k \ln\left(\frac{V_1}{V_2}\right)^{E/h\nu}, \end{aligned} \qquad (15)$$

where the value of the Wien constant β was taken from (9).

Einstein then follows up the derivation of the result (15) by a detailed calculation of a similar entropy difference for a classical ideal gas of n molecules. For this he exploits the 'Boltzmann Principle' $S = k \ln W$ relating entropy to statistical probability; omitting the details of his argument, he arrives at the result [2]

[2] The entropy of a classical ideal gas of n particles has the form

$S(E,V) = nk(\ln V + 3/2 \ln (2E/3nk))$

While the volume dependence is similar to that in (14), the energy dependence is quite different.

$$S(E,V_1) - S(E,V_2) = k \ln\left(\frac{V_1}{V_2}\right)^n \qquad (16)$$

Comparison of the two results (15) and (16) leads to his profound conclusion:

"...We (further) conclude that 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 $h\nu$".

(Einstein actually wrote $R\beta\nu/N$ for this last expression, which is just $h\nu$). Note carefully the explicit mention that this refers to radiation in the Wien limit; indeed the use of the complete Planck Law *does not* lead to such a result! Note also the conclusion that the energy quanta are mutually independent, reflecting the comparison being made to the classical ideal gas.

Thus was the concept of 'light quanta' first arrived at, with its stated limitations. Nevertheless, right away Einstein abstracts the key idea and boldly extrapolates it beyond these limitations to formulate his 'heuristic principle':

"If monochromatic radiation (of sufficiently low density) behaves, as concerns the dependence of its entropy on volume, as though the radiation were a discontinuous medium consisting of energy quanta of magnitude $h\nu$, then it seems reasonable to investigate whether the laws governing the emission and transformation of light are also constructed as if light consisted of such energy quanta". Thus he proposes that in the processes of emission and absorption and interaction of light with matter, the same particulate nature should be seen!

Einstein concluded his paper by applying his 'heuristic principle' to three experimental observations: the Stokes rule in photo luminiscence, the photoelectric effect, and lastly the ionization of gases by ultraviolet light. We look next briefly at some highlights of the second of these applications.

The Photo-Electric Effect

This effect was discovered accidentally by Heinrich Hertz in 1887 while studying sparks generated by potential differences between metal surfaces. (Remember at that time the electron was not yet known!). After Joseph John Thomson discovered the electron in 1897, he turned to the photo electric effect and in 1899 could state that it was the electron that was ejected when ultraviolet light shone on a metal surface. In experiments around 1902 Philip Lenard studied the dependence of the ejected electron's energy on the intensity and frequency of the incident radiation – independent of the former, increasing with the latter.

In his 1905 paper Einstein proposed the following 'simplest conception' for what happens: a light quantum transfers all its energy to a single electron, independent of other quanta present and disappearing in the process; the electron emerges from the metal surface carrying with it the photon's energy except for what it has to 'pay' to leave the metal. He then proposed the following famous and simple equation (in modern notation) for the maximum energy of the emitted electron:

$$E_{\max} = h\nu - P, \tag{17}$$

where ν is the frequency of incident radiation and P– the work function characteristic of the metal – the energy lost by the electron in the release process.

The most extensive series of experiments to test (17) were carried out by Robert Andrews Millikan in the decade upto 1915, even though he was extremely skeptical about the light quantum hypothesis itself. In his 1915 paper he said: "Einstein's photoelectric equation.... appears in every case to predict exactly the observed results.... Yet the semicorpuscular theory by which Einstein arrived at his equation seems at present wholly untenable". Many years later, in 1949, he reminisced in these words: "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".

We discuss reasons for the widespread opposition to the photon idea later; let us conclude this section by quoting from the 1921 Physics Nobel Award citation to Einstein: "... for his services to theoretical physics and in particular for his discovery of the law of the photoelectric effect".

Wave-Particle Duality, Photon Momentum

We saw that in 1905 Einstein worked only with the Wien limit of the Planck Law, not the latter in its entirety. In 1909 he went back to the Planck Law itself. As was mentioned earlier, in 1904 he had derived on his own the energy fluctuation formula on the basis of the canonical ensemble construction:

$$\begin{aligned}(\Delta E)^2 &\equiv \langle E^2\rangle - \langle E\rangle^2 \\ &= k\,T^2 \frac{\partial}{\partial T}\langle E\rangle. \end{aligned} \tag{18}$$

(We take temperature T and volume V as the independent variables, and leave implicit the dependences of the average energy $\langle E \rangle$ on these). Considering thermal radiation contained in the frequency range ν to $\nu + \Delta\nu$ and in a unit spatial volume, at temperature T, the Planck Law gives:

$$\begin{aligned}
\langle E \rangle &= \frac{8\pi\nu^2}{c^3}\ \Delta\nu \frac{h\nu}{e^{h\nu/kT} - 1}, \\
(\Delta E)^2 &= kT^2\ \frac{8\pi h\nu^3 \Delta\nu}{c^3}\ \frac{e^{h\nu/kT}}{(e^{h\nu/kT} - 1)^2}\ \frac{h\nu}{kT^2} \\
&= \frac{8\pi h^2 \nu^4 \Delta\nu}{c^3} \left(\frac{1}{(e^{h\nu/kT} - 1)^2} + \frac{1}{(e^{h\nu/kT} - 1)} \right) \\
&= \frac{c^3}{8\pi\nu^2 \Delta\nu} \langle E \rangle^2 + h\nu \langle E \rangle . \qquad (19)
\end{aligned}$$

At this point the reader is encouraged to check that if $\langle E \rangle$ had been given purely by the Rayleigh–Jeans expression (6), only the first term on the right would have been obtained; while if $\langle E \rangle$ was given solely by the Wien expression (4) only the second term on the right would have appeared. Recalling that the Rayleigh–Jeans Law is the unambiguous result of classical Maxwell wave theory and the equipartition theorem, while the Wien Law led to the light quantum hypothesis, we see in the energy fluctuation formula (19) a synthesis or duality of wave and particle aspects of radiation. In Einstein's words: "....It is my opinion that the next phase in the development of theoretical physics will bring us a theory of light that can be interpreted as a kind of fusion of the wave and the emission theories... (The) wave structure and (the) quantum structure... are not to be considered as mutually incompatible...."

Fourteen years later, in 1923, Prince Louis Victor de Broglie would suggest a similar particle-wave duality for the electron.

The next time Einstein turned to the Planck Law was in 1916 when he gave a new derivation of it based on Bohr's 1913 theory of stationary states of atoms (and molecules) and transitions between them accompanied by emission or absorption of radiation. In his work, Einstein introduced

"A splendid light has dawned on me about the absorption and emission of radiation"

Einstein to Michele Angelo Besso, November 1916

the famous A and B coefficients characterising the interaction between matter and radiation, and corresponding to the three distinct processes of absorption, induced emission and spontaneous emission of radiation by matter. Planck's radiation law was shown to be the result of equilibrium among these processes, given Bohr's postulates and the Boltzmann distribution for the numbers of molecules in the various energy or stationary states. While we will not reproduce this beautiful work here, let us mention that at the same time Einstein completed his physical picture of the light quantum – not only was it a localized parcel of energy $h\nu$, it was directed and carried a momentum $\frac{h\nu}{c}$ in its direction of motion as well. (Initial steps in this direction had earlier been taken by Einstein in 1909, by considering the momentum fluctuations of a mirror immersed in thermal radiation, as a result of fluctuations in the radiation pressure.) This result was derived by carefully analysing both energy and momentum balances when a molecule makes a transition from one energy level to another via emission or absorption of radiation, and demanding stability of the Planck distribution for radiation on the one hand, and of the Boltzmann distribution for molecules on the other.

It is interesting to realise that it took the discoverer of special relativity from 1905 to 1916 to complete the picture of light quanta. Remember though that the creation of the General Theory of Relativity had kept him busy upto November 1915.

In any case, with this additional insight into the kinematical properties of the light quantum Einstein was fully convinced of its reality. In 1917 he wrote to Besso: "With that, (the existence of) light quanta is practically certain". And two years later: "I do not doubt any more the *reality* of radiation quanta, although I still stand quite alone in this conviction".

Opposition to the Light Quantum – the Compton Effect

Why was there such prolonged and widespread reluctance to accept the idea of light quanta? In the cases of the electron, proton and neutron, all of which were experimental discoveries, the concerned particles were quickly accepted into the body of physics. But it was indeed very different with the photon.

One reason may have been Einstein's own sense of caution which he expressed in 1911 in this way: "I insist on the provisional character of this concept (light quanta) which does not seem reconcilable with the experimentally verified consequences of the wave theory". On several occasions people like Max von Laue, Arnold Sommerfeld and Millikan misinterpreted Einstein's statements to mean that he had gone back on his ideas! Apart from that the main reason seems to have been a near universal feeling that Maxwell's description of radiation should be retained as far as free radiation was concerned, and the quantum features should be looked for only in the interaction between matter and radiation. Indeed Planck said in 1907: "I am not seeking the meaning of the quantum of action (light-quanta) in the vacuum but rather in places where absorption and emission occur, and (I) assume that what happens in the vacuum is rigorously described by Maxwell's equations". And again in 1909: "I believe one should first try to move the whole difficulty of the quantum theory to the domain of the interaction between matter and radiation". It is also amusing to see what Planck and others said in 1913 while proposing Einstein for election to the Prussian Academy of Sciences: "In sum, one can say that there is hardly one among the great problems in which modern physics is so rich to which Einstein has not made a remarkable contribution. That he may sometimes have missed the target in his speculations, as, for example, in his hypothesis of light quanta, cannot really be held too much against him, for it is not possible to introduce really new ideas even in the most exact sciences without sometimes taking a risk".

The situation changed decisively only after the discovery of the Compton effect by Arthur Holly Compton in 1923. This is the scattering of a photon by a (nearly) free electron; the validity of the energy and momentum conservation laws convinced most skeptics of the reality of light quanta. The relation between the change in frequency of the photon and

"All the fifty years of conscious brooding have brought me no closer to the answer to the question, 'What are light quanta?' Of course today every rascal thinks he knows the answer, but he is deluding himself"

Einstein to Michele Angelo Besso, December 1951

the scattering angle is very simply calculable in the photon picture, and agrees perfectly with experiment; classical explanations do not work. (Today in the language of quantum field theory we say the incident photon is annihilated and the final photon with different frequency and momentum gets created, while the electron continues to exist throughout). In a popular article in 1924 Einstein remarked: "The positive result of the Compton experiment proves that radiation behaves as if it consisted of discrete energy projectiles, not only in regard to energy transfer but also in regard to Stosswirkung (momentum transfer)."

Except for one lone but important dissenter – Niels Henrik David Bohr. He continued to doubt the reality of light quanta, wanted to retain the Maxwellian picture of radiation, and to relegate quantum features exclusively to matter and not to radiation. As part of this line of thinking, in an important paper in 1924, Bohr and his coauthors Hendrik Anton Kramers and John Clarke Slater proposed giving up both causality and energy – momentum conservation in individual elementary processes, but retaining them only statistically. Fortunately these two ideas were experimentally tested right away – by Walther Bothe and Hans Geiger and by Compton and A W Simon respectively – and in both respects Bohr's proposals failed.

The light quantum idea was here to stay.

Bose Statistics – the Photon Spin

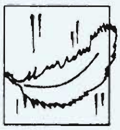
It was emphasized earlier that from the very beginning Einstein was conscious of the fact that there was no theoretically well founded derivation of the Planck Law (8). Even his own derivation of 1916 relied on the Bohr theory for matter and interaction processes between matter and radiation. In June 1924 Satyendra Nath Bose working at Dacca University (now Dhaka in Bangladesh) sent Einstein a four page paper containing a novel logically self-contained derivation of the Planck Law, treating thermal radiation as a statistical mechanical system on its own and taking the photon picture to its logical conclusion. Einstein immediately recognised the depth of Bose's ideas; helped in publishing his paper after translating it into German; and then followed it up with a paper of his own applying Bose's method to the ideal material quantum gas. The key point in Bose's method was a new way of counting complexions or microstates for an assembly of photons, in the process giving new meaning to the concept of identity of indistinguishable particles in the quantum world. In contrast to Einstein's conclusion drawn from the Wien Law that light quanta have a certain mutual independence, Bose statistics shows that photons – because of their identity in the quantum sense – have a tendency to clump or stick together. And basically this difference accounts exactly for the Planck Law and its difference from the Wien limit.

In his paper sent to Einsein, Bose apparently made another radical suggestion – that each photon has an intrinsic angular momentum or helicity of exactly one (quantum) unit, which could be either parallel or antiparallel to its momentum direction. But – revolutionary as he was – Einstein found this suggestion too revolutionary and removed it in the published version of Bose's paper!

Conclusion

Soon after the above events, modern quantum mechanics was discovered during 1925-26; and in 1927 Paul Adrien Maurice Dirac completed the task of quantising the classical Maxwell field, something which Einstein had foreseen as early as in 1917. And with that the photon was here to stay. What better way to end this account than to turn to Einstein himself in his old age:

"All the fifty years of conscious brooding have brought me no closer to the answer to the question, 'What are light quanta?' Of course today every rascal thinks he knows the answer, but he is deluding himself".



As far as the laws of mathematics refer to reality, they are not certain; and as far as they are certain, they do not refer to reality.

Albert Einstein

Suggested Reading

[1] **Abraham Pais, *Subtle is the Lord... The Science and the Life of Albert Einstein*", Oxford University Press, 1982.**

[2] **Max Born, *Natural Philosophy of Cause and Chance*, Clarendon Press, Oxford, 1949.**

[3] **John Stachel (editor), *Einstein's Miraculous Year*, Princeton University Press, 1998.**

[4] ***The Collected Papers of Albert Einstein* – Vol. 2 – The Swiss Years: Writings, 1900-1909; Vol. 6 – The Berlin Years: Writings, 1914-1917; Princeton University Press, 1989, 1997.**

[5] **N Mukunda, Bose Statistics – before and after, *Current Science* 66, 954–964, 1994.**

Address for Correspondence
N Mukunda
Centre for Theoretical Studies
and Department of Physics,
Indian Institute of Science,
Bangalore 560 012, India.
Email:
nmukunda@cts.iisc.ernet.in