

FROM THE HISTORY OF PHYSICS

PACS numbers: **01.65.+g**, **12.20.–m**, 14.70.Bh

One hundred years of the photon

V P Milant'ev

DOI: 10.1070/PU2005v048n11ABEH005819

Contents

Abstract. **The history of the origination of Einstein's hypothesis of light quanta is described. Reviewed is the arduous route of development of this hypothesis, which received ample recognition after the discovery of the photon.**

1. Introduction

The year 1905 was one of the most fruitful in Albert Einstein's creative career (1879 – 1955). Among the various ideas he expressed at that time was the idea of the existence of light quanta. For a rather long time, this idea was regarded as being fantastic, if not insane, and not meriting the attention of serious physicists like Max Planck (1858 – 1947), Niels Bohr (1885 – 1962), Hendrik Lorentz (1853 – 1928), and others. Despite Einstein's brilliant explanation of the photoeffect on the basis of his hypothesis of light quanta and the experimental confirmation of the basic photoelectric equation, this hypothesis was rejected by many physicists as being at variance with the well-known laws of electrodynamics. It was not until the experiments of Arthur Compton (1892 – 1962), performed in 1922 – 1923, that the existence of light quanta, later termed photons, was proven conclusively. The present paper is concerned with the history of the hypothesis of light quanta, its development, and recognition after Compton's brilliant experiments. The history of the subsequent discoveries of many remarkable properties of the photon and their related physical effects and modern realms of physics, like quantum electrodynamics, quantum optics, photonics, etc., is a subject deserving special consideration.

The quantum era in physics began after Planck first reported on 14 December 1900 about his introduction of *elements of energy* and the *quantum of action* [1]. This day is justly regarded as the *birthday of quantum theory*. Somewhat later, Planck set forth his ideas in his paper "On the Law of Distribution of Energy in the Normal Spectrum" [2], in which he showed that the *element of energy* of radiation is $\varepsilon = h\nu$, i.e., the radiation energy is transferred in quanta — in discrete portions $h\nu$. It was a revolutionary step in the development of physics. The idea of energy quanta contradicted both mechanics and electrodynamics, but Planck saw no other way out.

There were two possible versions for explaining the propagation mechanism of the 'elements of energy': (i) on being radiated, the 'elements of energy' retain their individuality in propagation, (ii) every radiated element dissipates in space as it recedes from the source. The former version is incompatible with classical optics, which relies on the wave character of electromagnetic radiation propagation. Planck, who had been brought up in the spirit of good old classical physics, was, despite the revolutionary character of his discovery, its earnest keeper and, like many at that time, could not reconcile himself to the fact that the experimentally well-proven wave theory had a limited applicability domain. That is why Planck believed at first that emission and absorption take place in discrete portions, while the radiation itself is continuous.

The 1st Solvay Congress, which was held in Brussels in October 1911, saw a vigorous debate on the problems of quanta and radiation. All outstanding physicists of that time participated in the Congress. In his report [3], Planck expressed his views about the possibility of combining the wave and quantum aspects of radiation. In particular, he showed how classical statistical mechanics should be changed so as to yield not its consequential Rayleigh – Jeans law but the quantum radiation law he had discovered. Wilhelm Wien (1864 – 1928), one of the authors of heat radiation laws, came up with the following idea [3, p. 725]: if it is assumed that the emission occurs by quanta, this would lead us "*into conflict with the Maxwell equations, even though we agree to apply them only outside of the electron.*" He concluded: "*Consequently, we would be compelled to abandon the Maxwell equations in intraatomic effects.*" But Planck believed [3, p. 730] that there was no need to change the Maxwell equations for empty space: "*...I confirm the strict validity of the Maxwell – Hertz differential equations in empty space, which, needless to say, rules out the existence of discrete energy quanta in vacuum.*"

V P Milant'ev Department of Experimental Physics,
Peoples Friendship University of Russia,
ul. Miklukho-Maklaya 6, 117198 Moscow, Russian Federation
Tel. (7-495) 955 08 13. Fax (7-495) 952 11 86
E-mail: vmilantiev@sci.pfu.edu.ru

Received 10 June 2005
Uspekhi Fizicheskikh Nauk **175** (11) 1233 – 1242 (2005)
Translated by E N Ragozin; edited by A M Semikhatov

For many years to come, on the basis of different hypotheses, Planck would endeavor to explain the radiation propagation on the basis of wave concepts, and only in response to experimental facts was he compelled to abandon his efforts. Later, in his Nobel speech on 2 June 1920, estimating his work in this area, Planck said: "*When I look back to the time, already twenty years ago, when the concept and magnitude of the physical quantum of action began, for the first time, to unfold from the mass of experimental facts, and again, to the long and ever tortuous path which led, finally, to its disclosure, the whole development seems to me to provide a fresh illustration of the long-since proved saying of Goethe's that man errs as long as he strives*" [3].

Contrary to Planck, Einstein immediately realized the revolutionary character of the quantum idea introduced by Planck and elaborated it further. Appreciating the significance of Planck's discovery, Einstein wrote: "*...Planck's radiation law allowed the first accurate determination of absolute atomic sizes, independently of other assumptions. Furthermore, he brought out clearly that there exists, apart from the atomistic structure of matter, atomistic energy structure of a sort, which is governed by the universal constant introduced by Planck. This discovery has become the basis for all investigations in XXth century physics and since then has motivated its development almost completely. Without this discovery it would have been impossible to establish the true theory of molecules and atoms and of energy processes that control their transformations. Moreover, it destroyed the framework of classical mechanics and electrodynamics and set before science the task of finding the new cognitive basis for all physics*" [4].

2. How did the hypothesis of light quanta originate?

In 1905, in his work "On an Heuristic Viewpoint about the Emergence and Conversion of Light" [5], Einstein came up with the idea that the 'elements of energy' have special individuality and introduced the hypothesis of *light quanta*. In the introduction to this paper, Einstein wrote: "*... despite the ample experimental corroboration of the theory of diffraction, reflection, refraction, dispersion, etc., it may turn out that the theory of light, which operates on continuous spatial functions, will give rise to contradictions with experience when applied to the effects of light emergence and conversion. I do believe that experiments relating to 'blackbody radiation,' photoluminescence, generation of cathode rays under UV irradiation, and other groups of phenomena involving the emergence and conversion of light are better explicable by the assumption that the light energy is discretely distributed in space... . The energy of a light beam emanated from some point is not distributed continuously over the progressively increasing volume but is represented by a finite number of spatially localized indivisible energy quanta, which are absorbed or produced only as a whole... . The above reasoning, in my view, by no means refutes Planck's radiation theory; quite the reverse, it supposedly shows that Planck in his radiation theory introduced in physics a new hypothetical element — the hypothesis of light quanta.*"

To arrive at this conclusion, Einstein considered the entropy S of blackbody radiation occupying a volume V,

$$S = V \int_0^\infty \varphi_\nu(\rho_\nu)\,\mathrm{d}\nu\,,$$

where $\varphi_\nu\,\mathrm{d}\nu$ is the entropy and $\rho_\nu\,\mathrm{d}\nu$ is the energy of radiation in the frequency interval $(\nu, \nu + \mathrm{d}\nu)$. For definiteness, Einstein assumed that the radiation satisfies the well-known Wien law $\rho_\nu = a\nu^3 \exp(-b\nu/T)$, where a and b are empirical constants.

Because the entropy of blackbody radiation is maximal for a given energy (and constant volume),

$$\delta \int_0^\infty \varphi_\nu(\rho_\nu)\,\mathrm{d}\nu = 0$$

subject to the constraint that

$$\delta \int_0^\infty \rho_\nu\,\mathrm{d}\nu = 0\,.$$

By introducing a Lagrange multiplier λ, one can write these relations in the form

$$\int_0^\infty \left(\frac{\partial\varphi_\nu}{\partial\rho_\nu} - \lambda\right)\delta\rho_\nu\,\mathrm{d}\nu = 0\,.$$

Because $\delta\rho_\nu$ is arbitrary, it follows that the derivative $\partial\varphi_\nu/\partial\rho_\nu = \lambda$ is independent of the frequency. Einstein next calculated the entropy increase $\mathrm{d}S$ for a constant volume, when the temperature reversibly changes by $\mathrm{d}T$:

$$\mathrm{d}S = V \int_0^\infty \left(\frac{\partial\varphi_\nu}{\partial\rho_\nu}\,\mathrm{d}\rho_\nu\right)\mathrm{d}\nu = \frac{\partial\varphi_\nu}{\partial\rho_\nu}\,\mathrm{d}\left(V\int_0^\infty \rho_\nu\,\mathrm{d}\nu\right) = \frac{\partial\varphi_\nu}{\partial\rho_\nu}\,\mathrm{d}E\,,$$

where

$$E = V \int_0^\infty \rho_\nu\,\mathrm{d}\nu\,.$$

Because the process is reversible and the volume is constant, $\mathrm{d}E = T\,\mathrm{d}S$. It follows from this and from the previous equality that $\partial\varphi_\nu/\partial\rho_\nu = 1/T$. By determining $1/T$ from Wien's law, it is possible to derive the relation

$$\frac{\partial\varphi_\nu}{\partial\rho_\nu} = -\frac{1}{b\nu}\ln\frac{\rho_\nu}{a\nu^3}\,.$$

Upon integration, in view of the condition $\varphi_\nu = 0$, it follows for $\rho_\nu = 0$ that

$$\varphi_\nu(\rho_\nu) = -\frac{\rho_\nu}{b\nu}\left(\ln\frac{\rho_\nu}{a\nu^3} - 1\right).$$

The energy E_ν of radiation into a unit frequency interval in the volume V is $E_\nu = V\rho_\nu$. The entropy of this radiation is given by

$$S_\nu = V\varphi_\nu(\rho_\nu) = -\frac{E_\nu}{b\nu}\left(\ln\frac{E_\nu}{aV\nu^3} - 1\right).$$

The entropy of equilibrium radiation with the same energy in another volume V_0 is

$$S_\nu^0 = V_0\varphi_\nu(\rho_\nu) = -\frac{E_\nu}{b\nu}\left(\ln\frac{E_\nu}{aV_0\nu^3} - 1\right).$$

Therefore, the entropy difference is

$$S_\nu - S_\nu^0 = k \ln \left(\frac{V}{V_0} \right)^{E_\nu/h\nu} .$$

Here, the constant b is, according to Planck, replaced by the ratio h/k, where h is the Planck constant and k is the Boltzmann constant. According to Boltzmann, the difference in entropy of states 1 and 2 is proportional to the natural logarithm of the ratio between the thermodynamical probabilities of these states, i.e., the logarithm of the relative probability of state 1 with respect to state 2. From the last relation, it follows that this probability is equal to $(V/V_0)^{E_\nu/h\nu}$.

Einstein next considered an ideal gas consisting of N molecules in a volume V_0. It is easy to determine the probability of all these N molecules accidentally finding themselves in a volume $V < V_0$. Owing to the independence of molecular motion, this probability is equal to $(V/V_0)^N$.

By comparing the two resultant expressions for the probabilities, Einstein arrived at the conclusion: "*From the standpoint of the heat theory, low-density monochromatic radiation* (*within the domain of applicability of the Wien radiation law*) *behaves as if it consisted of mutually independent quanta of energy as high as hν*." And next: "*This brings up the question: is the law of light emergence and conversion such that light consists of the like energy quanta?.. We have to assume that homogeneous light consists of energy grains — 'light quanta,' i.e., small portions of energy scudding across empty space with the velocity of light*" [5]. These notions are completely incompatible with Maxwell's electrodynamics, which was noted, naturally, by Einstein himself: "*...to Planck's quanta one has to ascribe distinctive direct reality and, as regards energy, the radiation should therefore possess molecular structure of a sort, which, of course, is at variance with Maxwell's theory*" [5].

From Einstein's hypothesis about light quanta, there naturally arose another problem — the problem of the wave–corpuscle dualism. In 1909, in his paper "On the Present Status of the Radiation Problem" [6, p. 164], Einstein for the first time pointed to the dual nature of light. He calculated the energy fluctuations of equilibrium radiation in a volume V for a temperature T. If E is the instantaneous value of the radiation energy in the frequency interval $(\nu, \nu + \mathrm{d}\nu)$, for a root-mean-square energy fluctuation $\overline{(\Delta E)^2}$ Einstein obtained the formula

$$\overline{(\Delta E)^2} = h\nu \bar{E} + \frac{c^3}{8\pi\nu^2 V \mathrm{d}\nu} \bar{E}^2 .$$

The second term on the right-hand side is, as shown by Einstein, due to the interference of partial waves, in complete agreement with Maxwell's theory of light. The first term is totally inexplicable from this standpoint, but it becomes perfectly understandable if one accepts the hypothesis of light quanta. Then, the quanta, like the particles or molecules of an ideal gas, should obey the statistical laws of molecular kinetic theory. In this case, the calculated value of energy fluctuation is in complete agreement with the first term. Therefore, the calculation performed was the first indication of the wave–corpuscle dualism of light. (Einstein made a report on this subject to the aforementioned Solvay Congress in 1911.) The existence of the two terms of different nature in the formula for radiation energy fluctuations actually turned out to be a consequence of Planck's formula. The original derivation of the famous Planck formula with the aid of interpolation already implied combining the corpuscular and wave notions of light. Einstein was perfectly aware of this. Indeed, Planck showed that the second derivative of the entropy with respect to the oscillator energy $\partial^2 S/\partial U^2$ is determined by different formulas: $\partial^2 S/\partial U^2 = \mathrm{const}/U$ when using the Wien radiation law (corpuscular notions of light) and $\partial^2 S/\partial U^2 = \mathrm{const}/U^2$ when using the Rayleigh–Jeans formula (wave notions). Planck's brilliant conjecture consisted in combining both these expressions with the aid of the interpolation formula

$$\frac{\partial^2 S}{\partial U^2} = \frac{a}{U(b+U)} ,$$

which led to the Planck formula [1, 7]. In his paper Ref. [6, p. 164], Einstein wrote: "*My intention here was only to show how deep are the roots of the problems the radiation formula implicates us in, even though we may view it as something given empirically*."

In an in-depth analysis of the subsequent refined derivation of Planck's formula [1], Einstein excoriated this derivation [8] by exposing its inconsistency, for Planck simultaneously accepted and rejected classical electrodynamics. On the one hand, Planck did use the formula for the spectral radiation density

$$\rho_\nu(T) = \frac{8\pi\nu^2}{c^3} u(\nu, T) ,$$

which he rigorously obtained on the basis of classical electrodynamics, whereby it is assumed that the oscillator energy changes continuously. On the other hand, in the statistical consideration of the interaction between oscillators with different eigenfrequencies, Planck arrived at the formula

$$u = \frac{h\nu}{\exp(h\nu/kT) - 1} ,$$

in the derivation of which the same oscillator energy was treated as a discrete quantity, which takes only values multiple of $h\nu$. Not denying the validity of Planck's formula itself, in the inconsistency of its derivation Einstein saw an incentive for the subsequent development of the radiation theory. It was a thorough analysis of this problem that led Einstein to the hypothesis of light quanta.

Einstein's hypothesis was hotly disputed by Planck in 1911: "*When one ponders over the ample experimental confirmation which Maxwell's electrodynamics has received in the investigation of even the most intricate interference phenomena, when one thinks about the extraordinary difficulties which all theories would have to encounter in the explanation of electric and magnetic phenomena in the event that they abandon this electrodynamics, one instinctively feels hostility against any attempt to shake its foundations. For this reason we set aside the hypothesis of 'light quanta' subsequently as well, the more so that this hypothesis is still at its infancy. All phenomena occurring in empty space will be considered to be perfectly consistent with Maxwell's equations and to bear no relation to the constant h*" [9] (see also Ref. [3, p. 282]). At that time, Niels Bohr adhered to the same opinion: "*Although this viewpoint is of considerable importance in understanding* *several classes of phenomena, for instance the photoelectric effect, the hypothesis under discussion may nevertheless not be considered as a satisfactory solution. As is well known, it is this hypothesis that leads to insurmountable difficulties in the interpretation of interference effects, which are the main means in the investigation of radiation properties. In any case, it is valid to say that the proposition underlying the hypothesis of light quanta is basically exclusive of the possibility of comprehending the notion of frequency ν, which plays the leading role in this theory. The hypothesis of light quanta is therefore unsuitable for providing the general picture of processes that might embrace the entire collection of effects considered in the applications of the quantum theory*'' [10, p. 518]. Bohr persistently disagreed with the hypothesis of light quanta and upheld nothing but the wave conceptions: ``*...despite its heuristic value, the hypothesis of light quanta, being totally inconsistent with the so-called interference effects, is unhelpful in elucidating the issue of radiation nature*'' [10, p. 523]. He was said to have remarked sarcastically on receiving a letter from Einstein, who clarified the significance of light quanta, that even if Einstein had sent a radiogram informing him that he was in possession of the final evidence for the reality of light particles, this ``*radiogram would have reached me by the radio, owing to waves*'' [11].

Later on, however, Einstein's hypothesis of light quanta came to be regarded as one of his most significant achievements. Bohr wrote about it in 1955: ``*The breadth of Einstein's scientific horizons and the straightforwardness of his mind have been demonstrated most clearly in the fact that, during those years when he gave the sweeping generalization of classical physics, he was perfectly aware of the fact that Planck's discovery of the universal quantum of action imposed certain limitations on such an approach. Einstein's amazing intuition led him to the notion of photons as energy and momentum carriers in individual radiation events. He thereby found the starting point for the elaboration of consistent quantum-theoretical methods, which allowed interpreting a huge body of experimental data pertaining to the properties of matter and, furthermore, led him to the necessity of revising our basic notions*'' [10, p. 479].

3. Applications of the light quanta hypothesis

Einstein did not restrict himself to only formulating the hypothesis of light quanta. First and foremost, he applied the idea of light quanta to explain the photoelectric effect.

This effect was accidentally discovered by Heinrich Hertz (1857 – 1894) in 1887 in the investigation of electromagnetic wave propagation from a radiating resonator to the receiver. To better see the jump spark in the radiator, Hertz screened the receiver, and then he found that the spark was initiated for a lower voltage across the electrodes. It turned out that the reason lay with screen irradiation by the light of an electric arc. At that time, Hertz was enthusiastic about proof of the existence of electromagnetic waves predicted by Maxwell. That is why Hertz did not take an interest in the discovered effect, which came to be the negation of the wave nature of light due to a quirk of fate. A year later, the photoelectric effect (or simply the photoeffect) was rediscovered by W Hallwachs (1859 – 1922), A Righi (1850 – 1921), and A G Stoletov (1839 – 1896). Hallwachs showed that a metal plate is positively charged under ultraviolet irradiation. Righi, who was the first to observe the photoeffect in dielectrics (ebonite, sulfur), came up with the term 'photocell.' The first photocell was made and practically employed by Stoletov. He also discovered the saturation photocurrent and one of the photoeffect laws — direct proportionality between the photocurrent and the incident light intensity. In 1899, J J Thomson (1856 – 1940), who discovered the electron in 1897, and P Lenard (1862 – 1947) determined the specific charge of the particles emanating from the surface of an illuminated body. This charge turned out to be the same as for cathode rays. Thus, it was proved that electrons are ejected from the illuminated surface. In 1902, Lenard determined that the ejected electron energy is completely independent of the incident light intensity and is a linear function of its frequency. This fact is impossible to explain on the basis of classical concepts. Indeed, in the context of classical concepts, an electron in a light field executes oscillations whose amplitude should increase with the wave intensity. The energy of electrons capable of escaping from the body surface should therefore increase. But this was not observed.

Employing the hypothesis of light quanta, in the eighth section of the same 1905 paper, Einstein obtained the energy balance equation for the photoeffect:

$$E_{\max} = h\nu - W\,,$$

where $E_{\max}$ is the highest energy of ejected electrons and W is the work function, i.e., the energy required to remove an electron from the material. From this formula, it follows that the highest photoelectron energy, in agreement with Lenard's finding, depends linearly on the frequency, the slope of the straight line $E_{\max}(\nu)$ being independent of the material's composition and determined only by Planck's constant. Taking this into consideration, Einstein noted for experimenters that the inhibitory potential should be a linear function of the exciting light frequency and plotted ``*in Cartesian coordinates as a straight line whose slope is independent of the nature of the substance under investigation.*'' Einstein wrote [5]: ``*As far as I know, our concept of the photoelectric processes does not contradict Lenard's observations. If a quantum of exciting light donates its energy independently of all other quanta, the electron velocity distribution... should not depend on the exciting light intensity; on the other hand, the number of electrons that escape from the body should be proportional, all other factors being equal, to the exciting light intensity.*''

Einstein's equation was first borne out in the experiments of A Hughes and O Richardson and of K Compton in 1912 (see the references in Ref. [11, p. 46]). The most conclusive experiments from the standpoint of precision (Fig. 1) were carried out by Robert Millikan (1868 – 1953) in 1914 – 1916 [12] (see also Ref. [12, p. 46]). Millikan subsequently wrote: ``*I spent 10 years of my life to verify this Einstein's equation of 1905, and despite all my expectations I had to unconditionally admit in 1915 that it is experimentally borne out despite its absurdity, for it seemed to contradict everything we know of the interference of light*'' [13]. This is one more indication that at that time many physicists regarded Einstein's hypothesis as a nearly crazy idea.

Prior to Einstein's work, Planck's quantum theory explained only blackbody radiation laws and was in no way concerned with other physical phenomena. The Einstein photoeffect theory showed for the first time the universal character of Planck's ideas and his constant of action. In 1907, in his paper ``Planck's Theory of Radiation and the Theory of Specific Heat'' [6, p. 134], Einstein extended quantum notions to molecular kinetic effects as well.

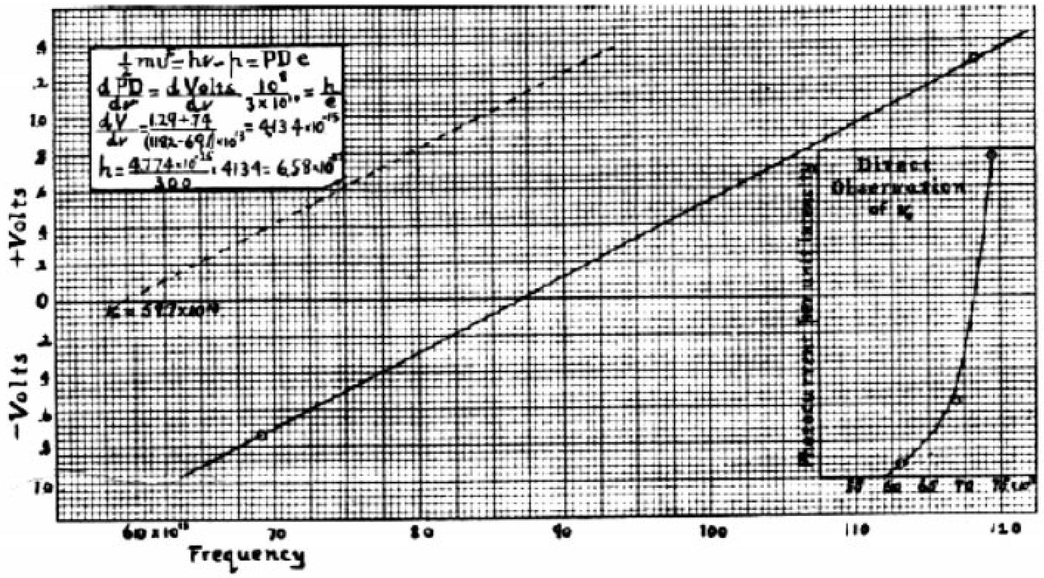

Figure 2:

$$p = hv_0 \qquad (3)$$

Now since both the independence of photo–emission upon temperature, and also the fact that gases show the photo–effect, indicate that the electrons which are ejected by light from metals are not the free electrons of the metal, but rather electrons which are constituents of the atoms, we would naturally consider p as made up of two parts, (1) the work p_1 necessary to detach the electron from its parent atom and make it a free electron of the metal, and (2) the work p_2 necessary to detach this free, or conduction, electron from the surface of the metal.

If we consider two opposed metal surfaces, for example one of pure zinc and one of pure copper separated only by the ether, and imagine that they have been put initially into the same electrical condition, so that no electrical field exists between them, then if a wire of copper be run from the copper plate to the zinc plate, we find by experiment that upon making contact an electric field is established between the plates. We say that the P.D. which now exists has arisen because of a contact. E.M.F. at the junction of copper and zinc which causes an electrical flow from copper to zinc until equilibrium is set up, and we measure this contact E.M.F. by the observed P.D. which it creates, taken of course with the opposite sign. By definition then the contact E.M.F. is the amount of work which, before any electrical field exists, would be required to transfer one unit of free positive electricity

8

Figure 1. Passage from Millikan's paper [12].

Referring to Planck's theory, which states that energy can be transferred only in portions that are multiples of hv, Einstein wrote in the above paper: "*However, I do not think we should be content with this result. In fact, this brings up the question: if the 'elementary things,' which are assumed to exist in theory and mediate energy exchange between matter and radiation, cannot be understood in the sense of present-day molecular kinetic theory, then should we not modify the theory also for* *other periodically oscillating things considered by the molecular theory of heat? In my opinion, the answer is obvious. If the Planck theory of radiation strikes the core of matters, we must expect to find also in other regions of the heat theory such contradictions between the present molecular kinetic theory and the experience, that have to be solved in the adopted way*.'' Einstein implied the then-existing problems relating to specific heat. For a long time, the law discovered by P L Dulong (1785–1838) and A T Petit (1791–1820) was considered to hold true. According to this law, the quantity of heat required to raise the temperature of one mole of any element in the solid state by 1 °C is equal to about 6 cal. The interpretation of Dulong–Petit's law relied on the classical theorem that energy is uniformly distributed over the degrees of freedom. However, specific heat measurements in very hard crystals, for instance diamond, at sufficiently low temperatures, which were carried out after 1872, showed that the specific heat decreases as the temperature is lowered. Attempts to explain these departures from the Dulong–Petit law did not meet with success for a long time. Einstein, who was the first to realize that the explanation should be sought with the aid of Planck's quantum ideas, made a supposition that quantization is the common property of oscillatory motion. Then, like electromagnetic radiation in empty space, the oscillatory motion of atoms (and ions) in crystals should, according to Einstein, be quantized as well: ''*Until now, the motion of molecules was believed to obey the same laws as does the motion of bodies from our everyday experience... now we are forced to assume that for oscillatory ions which can mediate energy exchange between matter and radiation, the manifold of states which they are able to take should be less than in the case of the bodies in our experience. We should in fact assume that the energy of the 'elementary thing' can take exclusively the values* 0, $h\nu$, $2h\nu$, *etc*.'' [6, p. 134]. Einstein determined that if a crystal has an oscillation mode with a frequency such that the corresponding energy quantum $h\nu$ is far greater than the thermal excitation energy, such an oscillation mode cannot be excited at this temperature. The thermal motion is then distributed not over all crystal oscillation modes but only over their low-frequency part. In this domain, every mode acquires the quantity of energy supposed by the theorem of uniform energy distribution, but the crystal as a whole receives less energy. This accounts for departures from the Dulong–Petit law.

In his calculations, Einstein neglected the interaction between the atoms of a substance, assuming that all atoms of a solid oscillate with the same frequency at a given temperature. Using Planck's formula, Einstein derived an expression for the energy of 1 mole, whence followed the formula for the specific heat of 1 mole:

$$c = 3R\left(\frac{h\nu}{kT}\right)^2 \exp\left(\frac{h\nu}{kT}\right)\left[\exp\left(\frac{h\nu}{kT}\right) - 1\right]^{-2}.$$

This formula agreed with experimental data rather well. As regards the departures from the data at very low temperatures, in 1911 Einstein attributed them to the fact that he had used an assumption of equal vibration frequencies of all atoms. Einstein's theory of specific heat of solids was subsequently refined by Petrus Debye (1884–1966), Max Born (1882–1970), and Theodore von Karman (1881–1963). This theory was brilliantly borne out by experiments.

The success of Einstein's theory of specific heat was of enormous importance at that time not only because it eliminated one of the contradictions in physics but also because it strengthened the belief of some doubting physicists that quantum theory was valid. For instance, in 1911, Walther Nernst (1864–1941) noted: ''*At present, the quantum theory actually is merely a calculation rule somewhat odd, if not grotesque, in nature; but Planck's works as far as radiation is concerned and Einstein's works as regards molecular mechanics have shown it to be so fruitful ... that science should treat it with full seriousness and subject it to careful examination*'' [11, p. 68].

Einstein was probably the first to realize that the hypothesis of light quanta was actually contained implicitly in the second quantum postulate of Bohr's atomic theory [14]. Elaborating Bohr's ideas and invoking the hypothesis of light quanta, in 1916 Einstein investigated the conditions for equilibrium between a molecular gas and radiation [6, pp. 386, 393]. He was the first to introduce probabilistic concepts into the radiation theory of atoms and molecules with the aid of *Einstein coefficients*, which define quantum transition probabilities, and provided a clear definition of possible transitions between quantum states.

Einstein considered the probability A_{mn} for the *spontaneous transition* per unit time from state m to state n (for $E_m > E_n$). The quantity A_{mn} has the meaning of the average number of emission events per unit time per one atom, $A_{mn} = 1/\tau_m$, where τ_m is the atomic lifetime in the excited state. Einstein introduced the coefficient A_{mn} thinking that a molecule can transit from one energy state to another, lower state ''*without external inducement*.'' The A_{mn} coefficient was later termed the spontaneous emission probability. Employing the correspondence principle, Bohr related the coefficient A_{mn} to the Fourier expansion coefficients of the dipole moment D_{mn}:

$$A_{mn} \leftrightarrow \frac{(2\pi)^4 \nu^3}{3c^3 h} |D_{mn}|^2 .$$

When an atom in a state E_n is placed in an external electromagnetic field with a frequency ω, it absorbs the field energy if this frequency coincides with the transition frequency $\omega_{mn} = (E_m - E_n)/\hbar$. As a result, the atom transits to the excited state E_m. Let ρ_ω be the spectral energy density of the electromagnetic radiation. A quantity $W_{nm} = B_{nm}\,\rho_\omega$ is introduced and endowed with the meaning of the radiation absorption probability for the atom per unit time. Along with the *absorption event*, which results in the $n \to m$ transition, Einstein envisaged the existence of the inverse process — *stimulated, or induced emission*. This process occurs in the $m \to n$ transition under the action of an external electromagnetic field whose frequency is equal to the transition frequency and is characterized by the quantity $W_{mn} = B_{mn}\,\rho_\omega$, which has the meaning of the stimulated emission probability per unit time. The coefficients A_{mn}, B_{mn}, and B_{nm} are referred to as the Einstein coefficients. They are bound together by the relations

$$g_n B_{nm} = g_m B_{mn} , \qquad A_{mn} = \frac{2\hbar\omega_{mn}^3}{\pi c^3}\,\frac{g_n}{g_m}\,B_{nm} .$$

The coefficient g_n (or g_m) is termed the statistical weight, or the degeneracy multiplicity of the nth (or mth) state.

Einstein's concepts of spontaneous and stimulated transitions relating to the emission and absorption of radiation turned out to be overwhelmingly important for the subsequent development of the radiation theory. These concepts later became the foundation for the development of masers and lasers.

Applying the concepts of transitions in the state of equilibrium between atoms and radiation, Einstein arrived at an elegant derivation of Planck's formula for the spectral radiation density ρ_ν. This was one more confirmation of Planck's quantum hypothesis.

Also vitally important in Einstein's paper [6, pp. 386, 393] was the examination of momentum transferred to the atom (or molecule) in the emission or absorption of light. Einstein wrote: "*...most important, in my opinion, is the conclusion about the momentum transferred to a molecule in spontaneous or stimulated emission... When a beam encounters a molecule and acts on it in such a way that the molecule acquires or loses by way of an elementary process some quantity of energy $h\nu$ in the form of radiation* (*stimulated emission*), *the molecule will inevitably gain the momentum $h\nu/c$ as well*: *in energy absorption — in the direction of beam propagation, and in emission — in the opposite direction... When a molecule loses energy without external excitation* (*spontaneous emission*), *this process is also directional. Spontaneous emission in the form of spherical waves does not exist. In an elementary process of spontaneous emission, the molecule acquires the recoil momentum equal to $h\nu/c$ in magnitude, while the direction is, according to the present status of the theory, determined only by* '*randomness*'." Appreciating keenly the results of this work, Bohr wrote many years later [10, p. 402]: "*Einstein emphasized quite expressively the fundamental nature of statistical description by indicating the analogy between the assumption that there exist spontaneous radiative transitions and the well-known laws that govern the transformations of radioactive substances... Einstein made the dilemma even more pointed by indicating that any radiation event should, if his reasoning is valid, possess a specific direction. This should be interpreted in the following sense*: *it is not only the light-quantum-absorbing atom that acquires from the photon a momentum whose direction corresponds to the direction of photon propagation, but it is also a radiating atom that gains momentum in the opposite direction, this being so despite the fact that a preferred direction in a radiation event is out of the question in the context of the wave picture*."

However, despite the successful experiments of Millikan and others, Einstein's hypothesis of light quanta did not enjoy the confidence of the physicists of that time. Quite typical is the following episode. Nominating Einstein for election to the Prussian Academy of Sciences in 1913, Planck, Nernst, H Rubens (1865–1922), and E Warburg (1846–1931) thus wrote in the conclusion of their recommendation: "*On the whole one may say that there hardly exists an important problem of contemporary physics in which Einstein has not made a substantial contribution. The fact that he sometimes does not hit the mark, like in the case of the hypothesis of light quanta, cannot be regarded as a negative argument, because it is impossible to advance a new idea, even in the most exact sciences, without taking certain risks*" [11, p. 54].

And the well-known physicist Charles Barkla (1877–1944) said, when receiving a Nobel Prize for the investigation of X-ray radiation properties in 1918, that his X-ray experiments suggest that emission and absorption are continuous and that only atoms emit light by quanta in some exceptional cases. Many physicists at that time believed that light quanta represent no physical reality and are no more than a felicitous heuristic way of defining some quantity of energy supposedly related to some property of electromagnetic fields, i.e., a light quantum was treated merely as some measure rather than a distinctive corpuscle. And in 1921, the Nobel Committee thus formulated its award of the Prize to Einstein: "*for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect*." In this case, not even a mention was made of either the discovery of light quanta or the construction of the relativity theory.

Nevertheless, as more and more new effects could be explained only in the context of quantum concepts, there occurred a slow and gradual recognition of the physical reality of quanta. The negative attitude of physicists to the hypothesis of light quanta is attributable to the fact that this hypothesis was bringing back the corpuscular notions of light. Everybody remembered well that the Newtonian corpuscular notions were resolutely abandoned after long-term discussions, because with their aid it was impossible to interpret either the light refraction law, or interference, or diffraction. Meanwhile, light quanta may not have anything in common with Newtonian light corpuscles. A light quantum is a distinct particle that propagates at the speed of light in empty space. The light quantum energy is $E = cp = h\nu$; in this case, the light quantum also has, along with the energy, the momentum $p = h\nu/c$. However, a light quantum would remain a hypothetical particle until its existence was proven in experiment.

4. Hypothetical light quantum becomes a photon

In the period between 1921 and 1924, it was noted in several experiments that the scattering of X-rays in matter gives rise to 'softer' X-rays, i.e., to longer-wavelength radiation. This was at variance with the radiation scattering theory developed by J J Thomson on the basis of classical notions in 1906. According to this theory, the electromagnetic radiation incident on an electron forces it to oscillate with the frequency of the incident radiation. The oscillating electron itself turns out to be a source of radiation, which is referred to as scattered radiation. The electron is said to scatter the incident radiation; in this case, the scattered radiation frequency should be the same as the incident radiation frequency.

Arthur Compton set himself the task of providing an explanation for the experimental evidence on X-ray scattering. No attempt to interpret it on the basis of classical notions met with success. Then, in 1923, proceeding from Einstein's hypothesis of light quanta, Compton supposed that "*when an X-ray quantum is scattered it spends all of its energy and momentum upon some particular electron*" [15].

It is pertinent to note that the idea of corpuscular properties of X-ray radiation was not unexpected for some experimenters. In particular, as early as 1911, W Bragg and H Porter stated thus: "*Energy considerations have directly led us to assume that X-rays and gamma-rays are corpuscular by nature, because every ray is a separate entity, which propagates through space without change in form and energy content, quite like a free particle would do*" [11, pp. 234, 235]. Late in 1912, Bragg wrote prophetically: "*...the problem now consists not in deciding between the two theories of X-rays but in finding... one theory possessing the capabilities of both of them*" [11, pp. 234, 235].

Compton investigated the scattering of hard X-ray radiation in media consisting of light elements (graphite, paraffin). In such media, the energy transferred to an atom

SCATTERING OF X-RAYS BY LIGHT ELEMENTS 495

the secondary. The zero point for the spectrum of both the primary and secondary X-rays was determined by finding the position of the first order lines on both sides of the zero point.

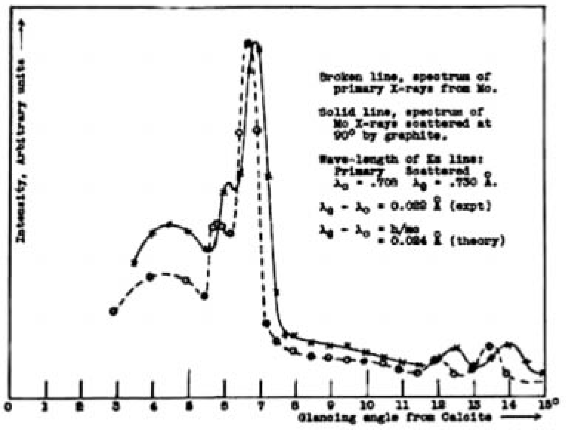

Fig. 4. Spectrum of molybdenum X-rays scattered by graphite, compared with the spectrum of the primary X-rays, showing an increase in wave-length on scattering.

It will be seen that the wave-length of the scattered rays is unquestionably greater than that of the primary rays which excite them. Thus the Kα line from molybdenum has a wave-length 0.708 A. The wave-length of this line in the scattered beam is found in these experiments, however, to be 0.730 A. That is,

$$\lambda_\theta - \lambda_0 = 0.022 \text{ A} \quad \text{(experiment)}.$$

But according to the present theory (Eq. 5),

$$\lambda_\theta - \lambda_0 = 0.0484 \sin^2 45^\circ = 0.024 \text{ A} \quad \text{(theory)},$$

which is a very satisfactory agreement.

The variation in wave-length of the scattered beam with the angle is illustrated in the case of γ-rays. The writer has measured[1] the mass absorption coefficient in lead of the rays scattered at different angles when various substances are traversed by the hard γ-rays from RaC. The mean results for iron, aluminium and paraffin are given in column 2 of Table I. This variation in absorption coefficient corresponds to a

[1] A. H. Compton, Phil. Mag. 41, 760 (1921).

Figure 2. Passage from Compton's paper [15].

by the radiation is greater than the electron binding energy in the atom. That is why these electrons can be treated as 'free,' barely bound to the atom. In this case, the X-ray radiation scattering in the medium reduces to scattering by a single electron. Compton's experiments demonstrated that the scattered radiation has two components, which depend on the scattering angle — one of them has the same wavelength as the incident wave and the other has a longer wavelength (Fig. 2). This phenomenon is referred to as the *Compton effect*. Compton and Debye showed that this effect is explicable only in terms of a collision of an X-ray quantum with a free electron. Using the energy and momentum conservation laws in the electron – photon system, Compton found that the wavelength of the radiation scattered due to the collision with the electron exceeds the incident radiation wavelength by $\Delta\lambda \equiv \lambda_f - \lambda_i = 2\lambda_C \sin^2 \theta/2$, where θ is the radiation scattering angle (Fig. 3). The new physical constant $\lambda_C = \hbar/m_0 c = 2.4 \times 10^{-10}$ cm received the name the *Compton length*. The formula Compton obtained was amply borne out by his experiments.

Summarizing the experiments conducted, Compton wrote: "*This remarkable agreement between our formulas and the experiments can leave but little doubt that the scattering of X-rays is a quantum phenomenon... The present theory depends essentially upon the assumption that each electron which is effective in the scattering scatters a complete quantum. It also involves the hypothesis that the quanta of radiation are received from definite directions and are scattered in definite directions. The experimental support of the theory indicates very convincingly that a radiation quantum carries with it directed momentum as well as energy*" [15].

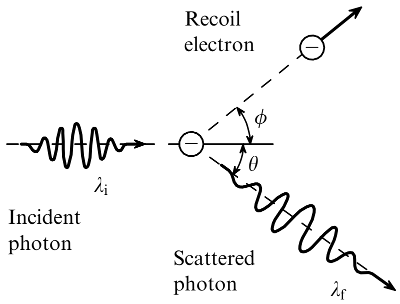

Figure 3. Compton scattering.

Einstein learned about Compton's experiments with satisfaction: "*The positive result of Compton's experiment shows that radiation behaves as if it were constituted by discrete corpuscles in the sense of not only energy transfer but of momentum transfer as well*" [16]. Therefore, Compton provided an experimental proof of the *existence of light quanta*. The implications of this discovery for physics were enormous. As noted by the famous German theoretical physicist F Hund (1896 – 1997), "*Bohr regarded the hypothesis of light quanta reservedly until 1922*," however, "*The physicists' attitude of inadmissibility or indifference changed after the discovery of the Compton effect*" [17].

Experiments that confirmed Einstein's hypothesis of light quanta were also carried out in 1924 by Russian physicists A F Ioffe (1880 – 1960) and N I Dobronravov. The American physicochemist G N Lewis (1875 – 1946) considered the notion 'light quantum' as being unfortunate, because "*we believe that it spends only a negligible part of its lifetime as the radiation energy carrier, while during the remaining time it is an important structural element inside an atom.*" That is why Lewis introduced a new term: "*...I will allow myself to propose the term photon for this hypothetical new atom, which is not light and yet substantially participates in all radiative processes*" [18].

This term was immediately accepted by physicists. The photon became a regular elementary particle with zero mass, zero electric charge, and spin equal to 1. However, the photon is a most peculiar particle. It is not a spatially localized object, and its position in space cannot be determined. The photon travels with the speed of light and therefore cannot stay at rest. Along with this, as shown by many experiments (photon density fluctuations in a light beam, selective photoeffect, etc.), the concept of polarization is applicable to an individual photon. Furthermore, as for electromagnetic waves, also observed for photons is the interference effect, this being so in the presence of only one photon [19]. Modern research shows that the interference of three, four, or five photons that are in *entangled quantum states* is also possible [20]. The de Broglie wavelength of an ensemble of *N* photons that are in such states is λ/N, where λ is the wavelength of a separate photon. By splitting single photons in a nonlinear crystal, it has been possible to produce *biphotons* ($N = 2$) [21]. Along with the spin angular momentum, photons are also characterized by orbital angular momentum [22]. According to modern experiments, the photon mass is close to zero with high precision: $m_\gamma < 10^{-51}$ g [23]. At the same time, theorists have already prepared equations that generalize the system of Maxwell equations to the case of a nonzero photon mass. Such equations were formulated by the Romanian physicist A Proca (1897 – 1955) in 1936 (see review Ref. [24]). The photon plays an extremely important part in modern physics. It serves as the carrier of electromagnetic interactions and is one of the 'truly fundamental' bosons [25].

After Compton's experiments, in 1924 Niels Bohr, Hendrik Kramers (1894 – 1952), and John Slater (1900 – 1976), when analyzing radiation – matter interaction and endeavoring to rescue the wave concepts, arrived at the conclusion that the energy and momentum conservation laws should merely be obeyed on average, statistically, rather than in every elementary interaction event [10, p. 526]. According to this theory, the radiation scattering should proceed continuously and the recoil electrons ejected quite stochastically, the wave scattering and the electron ejection being mutually uncorrelated. It was not long before Walther Bothe (1891 – 1957) and Hans Geiger (1882 – 1945) tested this hypothesis. Their experiments showed that the escape of about every eleventh radiation quantum coincides in time with the ejection of a recoil electron, whereas a purely random coincidence of these two events had to be expected, according to calculations, only in one of 10^5 cases. Hence, Bothe and Geiger drew the conclusion that their experimental data agree with Compton's findings and are contrary to the hypothesis advanced by Bohr, Kramers, and Slater. At the same time, Compton and A W Simon took advantage of the Wilson cloud chamber, which permitted determining both the time and escape direction of recoil electrons, to show that to every scattered radiation quantum there corresponded, on average, one recoil electron.

In 1950, similar experiments were performed with a high accuracy with the use of higher-grade instrumentation. Hofstadter and McIntyre [26] brought out clearly that "*The recoil electron and scattered photon are emitted together within a time interval of less than* 1.5×10^{-8} s." The experiments of Cross and Ramsey [27] suggested that the angle between the electron escape and the direction of the corresponding scattered photons differed by no more than $\pm 1^\circ$ from the angle defined by the conservation laws.

In other words, the energy and momentum conservation laws are fully applicable to the elementary event of particle interaction, as was supposed by Compton. Einstein and Wolfgang Pauli (1900 – 1958), who sacredly held to the strict conservation of energy and momentum, regarded the idea of Bohr, Kramers, and Slater as something like sedition. As regards this, Pauli said expressively: "*I deem it as good fortune that the concept of Bohr, Kramers, and Slater was so quickly refuted owing to the excellent experiments of Bothe and Geiger as well as to the recently published experiments of Compton. Of course, we are correct in believing that Bohr would not have adhered to this concept even if these experiments had not been staged. But many excellent physicists* (*like, for instance, Ladenburg, Mie, Born*) *would have adhered to it, and this unfortunate paper by Bohr, Kramers, and Slater would have probably become a drag on the progress of theoretical physics*" [13].

Bohr did realize his mistake before long and thus wrote in July of 1925 [10, p. 560]: "*The hope to obtain in this way the general formulation of the laws of the quantum theory would be groundless upon demonstration of the relation between individual atomic processes. In line with Einstein's quantum theory of light this relation imposes on us the corpuscular picture of light propagation. In the present state of affairs it is well to bear in mind that the desired generalization of classical electrodynamics will require a decisive reconsideration of the notions that have hitherto underlain the description of nature*." For the sake of justice it should be noted that 'the paper of the three' [13, p. 526] also stated that "*the wave nature of light propagation, on the one hand, and its absorption and emission in quanta, on the other, are those experimental facts which should form the basis of any atomic theory and which no explanations should be searched for*."

Thus, by 1925, it was definitely established that light behaves in several physical effects as an ensemble of particles with well-defined energy and momentum. On the other hand, numerous XIX-century experiments on interference, diffraction, and polarization of light demonstrated in an equally conclusive way that light possesses wave properties. This is how the acute problem of *wave – corpuscle dualism* emerged, which seemingly led physics into a dead end. This deadlock was overcome later, with the advent of the modern quantum theory. But this is quite another story, that of the "*drama of ideas*," according to Einstein.

References

1. Planck M *Verhandl. Deutsch. Phys. Ges.* **2** 237 (1900)
2. Planck M *Ann. Phys.* (Leipzig) **4** 553 (1901) [Translated into Russian: *Izbrannye Trudy* (Selected Works) (Moscow: Nauka, 1975) p. 251]
3. Planck M *Izbrannye Trudy* (Selected Works) (Moscow: Nauka, 1975) p. 282
4. Khramov Yu A *Fiziki. Bibliograficheskii Spravochnik* (Physicist. Bibliographic Reference Book) 2nd ed. (Ed. A I Akhiezer) (Moscow: Nauka, 1983) p. 216
5. Einstein A *Ann. Phys.* (Leipzig) **17** 132 (1905) [Translated into Russian: *Sobranie Nauchnykh Trudov* (Collected Scientific Works) Vol. III (Moscow: Nauka, 1966) p. 92]
6. Einstein A *Sobranie Nauchnykh Trudov* (Collected Scientific Works) Vol. III (Moscow: Nauka, 1966) p. 164
7. Milant'ev V P *Fizicheskoe Obrazovanie Vuzakh* **8** (1) 10 (2002)
8. Einstein A *Ann. Phys.* (Leipzig) **20** 199 (1906) [Translated into Russian: *Sobranie Nauchnykh Trudov* (Collected Scientific Works) Vol. III (Moscow: Nauka, 1966) p. 128]
9. Gliozzi M *Storia della Fisica* (Torino: Utet, 1965) [Translated into Russian (Moscow: Mir, 1970)]
10. Bohr N *Izbrannye Nauchnye Trudy* (Selected Scientific Works) Vol. II (Moscow: Nauka, 1971) p. 518
11. Jammer M *The Conceptual Development of Quantum Mechanics* (New York: McGraw-Hill, 1966) [Translated into Russian (Moscow: Nauka, 1985) p. 187]
12. Millikan R A *Phys. Rev.* **7** 18 (1916)
13. Dorfman Ya G *Vsemirnaya Istoriya Fiziki s Nachala XIX do Serediny XX vv.* (World History of Physics from the Beginning of XIXth to the Middle of XXth Century) (Moscow: Nauka, 1979)
14. Bohr N *Izbrannye Nauchnye Trudy* (Selected Scientific Works) Vol. I (Moscow: Nauka, 1970) p. 84; Milant'ev V P *Usp. Fiz. Nauk* **174** 209 (2004) [*Phys. Usp.* **47** 197 (2004)]
15. Compton A H *Phys. Rev.* **21** 483 (1923)
16. Einstein A "Das Komptonsche Experiment. Ist die Wissenschaft um ihrer selbst willen da?" *Berliner Tageblatt* (April, 20) (1924) [Translated into Russian: *Usp. Fiz. Nauk* **128** 533 (1979); *Sobranie Nauchnykh Trudov* (Collected Scientific Works) Vol. III (Moscow: Nauka, 1966) p. 58]
17. Hund F *Geschichte der Quantentheorie* (Mannheim: Bibliographisches Institute, 1967) [Translated into English: *The History of Quantum Theory* (New York: Harper and Row, 1974); Translated into Russian (Kiev: Naukova Dumka, 1980)]
18. Lewis G N *Nature* **118** 874 (1926)

19. Klyshko D N *Usp. Fiz. Nauk* **164** 1187 (1994) [*Phys. Usp.* **37** 1097 (1994)]
20. Mitchell M W, Lundeen J S, Steinberg A M *Nature* **429** 161 (2004); Walther P et al. *Nature* **429** 158 (2004); Zhao Z et al. *Nature* **430** 54 (2004)
21. Edamatsu K, Shimizu R, Itoh T *Phys. Rev. Lett.* **89** 213601 (2002)
22. Leach J et al. *Phys. Rev. Lett.* **88** 257901 (2002)
23. Luo J et al. *Phys. Rev. Lett.* **90** 081801 (2003)
24. Tu L-C, Luo J, Gillies G T *Rep. Prog. Phys.* **68** 77 (2005)
25. Mukhin K N, Tikhonov V N *Usp. Fiz. Nauk* **171** 1201 (2001) [*Phys. Usp.* **44** 1141 (2001)]
26. Hofstadter R, McIntyre J A *Phys. Rev.* **78** 24 (1950)
27. Cross W G, Ramsey N F *Phys. Rev.* **80** 929 (1950)