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CENTENARY OF FIVE FUNDAMENTAL EINSTEIN'S PAPERS

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Abstract

Five Einstein's fundamental papers, published in 1905, are reported, namely the paper on the photoelectric effect, where the concept of photon was introduced, the paper on Brownian movement, where Einstein proved that this movement is the consequence of the atomic hypothesis, his doctoral dissertation on the sizes of molecules, the paper on electrodynamics of moving bodies, containing the principles of special relativity theory, and the paper on the principle of the mass and energy equivalence. The consequences of these papers on the development of 20$^{\text{th}}$ century physics are discussed.

1 1. Introduction

In 1905 Albert Einstein published four scientific papers in the journal *Annalen der Physik*. Three of them appeared in the 17th volume, and the fourth one in the 18th volume of that journal; the fifth one appreared in 1906 in the 19th volume of *Annalen.* In the first paper Einstein explained the photoelectric effect, in the second one, on Brownian movement, he proved the real existence of atoms, in the third one he formulated the foundations of the special relativity theory, and in the fourth one he derived the law of the mass and energy equivalence from the principles of special relativity.

The problem of the laws of emission and absorbtion of radiation, the question of the existence of atoms and the search for the laws of the electrodynamics of moving bodies together with the problem of the existence of ether, appeared in physics at the close of 19th century.

2 The juvenile Einstein's papers

In his juvenile years Einstein was especially interested in the problem of the existence of ether. During his studies at the Federal Technical University in Zürich and during the years of his employment at the Federal Patent Office in Bern he studied the fundamental contemporary textbooks in physics, namely H.A.Lorentz', *Versuch einer Theorie der elektronischen und optischen Erschrichnungen in bewegten Körpern* (Attempt of the theory of electric and optic phenomena in moving bodies) (1895)[1], P. Drude's *Physik des Aethers auf elektromagnetischer Grundlage* (Physics of the ether on electromagnetic base) (1894) and his *Lehrbuch der Optik* (Textbook of optics) (1900), Ostwald's *Lehrbuch der allgemeinen Chemie* (Textbook of general chemistry) (1893), H. Poincaré's *Science et l'hypotese* (1869) and E. Mach's *Mechanik in ihrer historischen Entwickling* (Mechanics in its historical development) (1889).

During his studies in Zürich Einstein held frequent and vivid discussions on the current problems of physics with his friends, Michael Besso, Marcel Grossman, Leonard Habicht and Maurice Solovine. The participants of these discussions called them "Academia Olimp".

[1](Translation from German was made by the author)

During his studies on electrodynamics of moving bodies Einstein gradually approached the opinion, that the concept of ether is superfluous, and he came up to the ideas he formulated in 1905 as the special relativity theory.

In these years Einstein was also interested in atomic physics. In 1901 he published the paper *Folgerungen aus der Kapillaeritatserscheinungen* (Consequences from the phenomena of capillarity) [1], in which he attempted to determine the forces between atoms acting in the phenomenon of capillarity.

The five Einstein's papers published a century ago resulted from his years-long investigations and discussions.

3 Photoelectric effect

The editor of *Annalen der Physik* received Einstein's paper *Über einen der Erzeugung und Verwandlung des Lichtes betreffenden Gesichtspunkt* (On the point of view concerning production and conversion of light) [2] on March 18, 1905. The paper appeared on June 9 in the 17$^{\text{th}}$ volume of the journal. In the paper Einstein explained the laws of the photoelectric effect basing on the hypothesis of quanta of light.

The photoelectric effect was observed in 1887 by Heinrich Hertz and described in the next year by Wilhelm Hallwachs, who stated, that the zink plate used as the cathode in the discharge tube, irradiated by ultraviolet light, emitted electric charges which could be collected on the anode. In 1889 Julius Elster and Hans Geitel showed that these charges are deflected by magnetic field and they form electric current even when there is vacuum in the discharge tube.

In the years 1899–1992 Philippe Lenard stated, that the ratio of charge to mass for the particles of this current is equal to that of electrons. In his paper *Über lichtelektrische Wirkung* (On the photoelectric action) [3] he formulated the laws of the photoelectric effect. Two of them, namely that:

1. there exists the treshold frequency of the incident light, beneath which the effect doesn't occur,
2. the maximum kinetic energy of photoelectrons doesn't depend on the intensity of the incident light,

were inconsistent with the 19^{th} century wave-theory of light. (Lenard obtained the Nobel Prize in physics in 1905 *for his work on cathode rays*) [4].

Let us remark that in these years many more phenomena were known, incompatibile with the 19^{th} century theory of light, according to which light was emitted and absorbed continuously. The spectral distribution of the black body emission spectrum was one of them. In order to explain this spectrum Max Planck assumed in 1900, that light is emitted and absorbed in a discontinuous way, by "quanta of light". Every quantum carries the energy $E = h\nu$, where h is "the Planck constant", and ν is the frequency of emitted or absorbed light. Planck obtained the right formula for the energy distribution of the radiation emitted by the black body. (He obtained the Nobel Prize in physics in 1918 *for the introduction of the light quanta in physics*) [5].

Einstein extended Planck's hypotesis. In his paper on the photoelectric effect [2] he wrote: *It seems to me, that the observations of the black body radiation, photoluminescence, production of cathode rays by ultraviolet light, and other groups of effects concerning production or conversion of light, appear to be comprehensible, if we assume, that the energy of light is discontinuously distributed in space. According to this assumption, the light ray does not spread into bigger and bigger regions, but is composed of a finite number of point-wise localised quanta of energy, which move without splitting, and can be emitted and absorbed only as the whole.*

Therefore, according to Einstein, light is not only emitted and absorbed in quants, but also propagates in space as a set of quants.

In the same paper Einstein explained the photoelectric effect by applying to it the hypothesis of light quanta ("photons"). In the photoeffect the energy $h\nu$ of the photon absorbed on the surface of the metal transforms into the work P necessary to get the electron from the metalic surface layer and into the kinetic energy E_{kin} of the ejected electron

$$h\nu = P + E_{kin}$$

(Einstein's formula).

The exact verification of Einstein's formula was performed in 1916 by Robert Millikan [6], who obtained the Nobel Prize in 1923 *for his* *work on the elementary charge of electricity and the photoelectric effect* [7].

Einstein's paper [1] initiated investigations in quantum theory of light. In one of his next papers Einstein stated, that a photon should not only posess its energy, but also its momentum. Einstein's papers led to a new inconsistency: of light as a wave or of light as a set of photons. This inconsistency was removed twenty years later by Dirac's quantum theory of radiation (in 1928), which united both views on the nature of light, in one, but non-visual, abstract theory. This theory was developed by Sin-Itiro Tomonaga, Julian Schwinger, Richard Feynman and Freeman Dyson into quantum electrodynamics.

Einstein's paper on photoelectric effect had also other, non less important consequences. Together with the planetary model of athom (Rutherford, 1911), it opened the way to Niels Bohr's theory of hydrogen atom (1913), and in the twenties of 20^{th} century to the formulation of quantum mechanics. However, Einstein, like two of the founders of quantum mechanics, Louis de Broglie and Erwin Schoedinger, accepted the critical view towards the Born's interpretation of the wave function based on the concept of probability. Einstein also opposed Niels Bohr's and Werner Heisenberg's "Copenhagen Interpretation" of quantum mechanics.

Einstein considered quantum mechanics an incomplete theory. He expressed his opinion in a paper entitled *Can Quantum Mechanical Description be Complete?,* [8] published in 1935 together with Borys Podolsky and Nathan Rosen. Arguments quoted in this paper provoked a long and still not finished polemics concerning the foundations of quantum mechanics.

4 Brownian movement

The second Einstein's paper was received by the editor of *Annalen der Physik* on May 11^{th}, 1905, and was published on July 18^{th} of that year in its 17^{th} volume, under the title: *Über die von der molekularkinetischen Theorie der Waerme erforderte Bewegung von in ruhenden Fluessigkeiten suspenlierten Teilchen* (On the motion of particles suspended in resiting liquids demanded by the molecular-kinetic theory of heat) [9]. In this paper Einstein published the theory of Brownian movement.

The phenomenon, consisting in incessant, irregular motions of small particles suspended in liquids, was discovered in 1827 by an English botanist, Robert Brown. (Brownian movement of particles suspended in gases were discovered by a Lvov physicist, Łukasz Bodaszewski, in 1882) [10].

Brownian movement was scrupulously investigated in 19^{th} century, and many explanations were proposed. In one of them, in 1888 G. Gouy conjectured, that irregular motions of the suspended particles arise form irregularities in the thermal motions of the molecules of the medium. The phenomenon of the Brownian movement was explained in the first years of 20^{th} century by Albert Einstein and Marian Smoluchowski, because they independently pointed to the measurable quantity in this effect, namely to the mean square of displacement of the suspended particle, and they calculated this quantity. Before physicists attempted to measure the velocity of a particle suspended in a liquid medium. The path of such a particle has an immense number of fracture points, placed very dense; then one cannot talk about the velocity of the particle in the macroscopic sense.

Marian Smoluchowski was busy with the theory of Brownian movement since 1900, but he did not publish the results of his investigations, because he waited for experimental results to verify his formula for the mean square displacement of the suspended particle. When in 1905 and in 1906 Einstein published his two papers on Brownian movement, Smoluchowski decided to publish his theory in 1906. Its tittle was: *Zur kinetischen Theorie der Brownschen Molekularbewegung und der Suspensionen* (On kinetic theory of Brownian motion and of suspensions) [11].

The methods of argumentation in Einstein's and Smoluchowski's papers were quite different. In paper [9] from 1905 Einstein assumed general laws of statistical mechanics, and considered the osmotic pressure in the phenomenon of diffusion, which caused displacements of suspended particles. He calculated their mean square displacement. But Einstein was not sure whether he really considered Brownian movement. In the introduction to his paper [9] he remarked: *it is possible that the considered motions are identical with the so-called Brownian movement, but the data, accessible to me, are so inexact that I could not decide about them.*

No sooner than having received the letter from H. Siedentopf, who collaborated with Richard Zsigmondy from Goettingen, Einstein wrote his paper *Zur Theorie der Brownschen Bewegung* [12] (On the theory of Brownian movement), received by *Annalen* on December 6, 1905 and published in 1906, in which he stated that in fact he had considered Brownian movement.

Smoluchowski considered Brownian movement on the base of Guy's hypothesis. He investigated the in detail mechanism of the collisions of a suspended particle with the molecules of the medium. (In order to simplify the calculations he considered gaseous medium).

Einstein and Smoluchowski both obtained the formula for the mean square displacement $\sqrt{\overline{\Delta^2}}$ of the particle of suspension in the time interval $(0, t)$:

$$\sqrt{\overline{\Delta^2}} = \alpha\sqrt{\frac{RT}{3\pi r\eta N}t},$$

$\alpha = 1$, Einstein
$\alpha = \sqrt{\frac{64}{27}} = 1.54$, Smoluchowski,

R is gas constant, T – temperature in kelvins, N – Avogadro's number, η – viscosity coefficient, r – radius of the suspended particle. Smoluchowski's value of the constant α was a result of approximations accepted by him in his calculations. Smoluchowski agreed that Einstein's value of the coefficient α, equal to 1, was correct.

In 1924 F. Zeilinger calculated the quantity $\sqrt{\overline{\Delta^2}}$ by applying Smoluchowski's method and by taking into account all the effects which contributed to the collisions of the suspended particle with the molecules of the medium. He obtained the result identical with that of Einsten's ($\alpha = 1$).

In this paper Einstein considered the rigid, not-dissociated spherical molecules dissolved in a liquid, and investigated their diffusion by applying the equations of hydrodynamics of viscous fluids and by using the results of his paper [9].

The here mentioned papers of Einstein's and Smoluchowski's had as their background a sharp controversion, which broke out at the close of 19^{th} century between atomists and their adherents of the school of energeticists, who denied the existence of athoms.

A chemist Wilhelm Ostwald and a physicist and philosopher Ernst

Mach were the leaders of the energeticists school. Because of the agressive attitude of energeticists, talking about atoms was not popular in those years. The leader of the atomists Ludwig Boltzmann wrote in 1898 in the introduction to the second volume of his textbook *Vorlesungen über Gastheorie* (Lectures on the theory of gases), that the aim of his book was to save the results of the theory of gases for future generations. Ludwig Boltzmann died in 1906, before atomism became generally accepted again. But the papers of Einstein and Smoluchwski's together with experimental investigations of Richard Zsigmondy, Theodor Svedberg, Jean Perrin resulted in the victory of athomists. Wilhelm Ostwald accepted the real existence of atoms in 1909 [13]. Ernst Mach denied their existence until his death.

5 Sizes of molecules

Einstein's method of investigation of the phenomenon of diffusion, developed in [9], permitted him to calculate the sizes of big chemical molecules. He calculated them in his doctoral dissertation entitled *Eine neue Bestimmung der der Molekulardimensionen* (The new determination of the dimensions of molecules) [14], delivered to Zurich University and accepted by the editor of *Annalen der Physik* on August 19, 1905, supplemented in January 1906 and published on February 8, 1906.

Applying his method to the solutions of sugar Einstein obtained the sizes of sugar molecules, and Avogadro's number compatible with the values obtained by other methods.

6 Special relativity theory

The editor of *Annalen der Physik* received Einstein's paper *Zur Dynamik bewegeter Koerper* (On the dynamics of moving bodies) [15] on June 16, 1905. The paper appeared on September 29, 1905 in the 17$^{\text{th}}$ volume of *Annalen.* In this paper Einstein presented the foundations of the special relativity theory. He solved the difficulties which emerged in the electrodynamics of moving bodies at the end of 19$^{\text{th}}$ century.

Electrodynamics of resting bodies met with successes, for instance in the discovery of electromagnetic waves, but the attempts to generalise it to the case of quickly moving bodies failed.

Even worse, the foundations of electromagnetism and of Newtonian mechanics were inconsistent.

Newtonian mechanics is based on the Galilean relativity principle, according to which it is not possible to state experimentally, which of inertial frames of reference is resting, and which is moving. This principle expresses the fact, that all inertial frames of reference are equivalent, in each of them the laws of mechanics are identical.

On the contrary, in electromagnetics of that time it was assumed, that electromagnetic waves must propagate in some medium (called the ether). It was clear, that the frame of reference which is resting in relation to the ether, the laws of electromagnetism should be particularly simple. If the source of electromagnetic waves is resting in relation to the ether, the velocity of electromagnetic waves should be identical in all directions.

But if this source moves towards the ether, the velocity of electromagnetic waves should be different in different directions. Therefore the measurement of the velocities of light waves in different directions should allow to determine the velocity of the source towards ether. The crucial experiment was performed in 1887 by Albert Michelson and Edward Morley. They found, that the velocity of light in arbitrary frame of reference doesn't depend on the direction of light propagation. The attempts of determining the hypothetical resting frame of reference failed. In short: in Newtonian mechanics all frames of reference are equivalent, in electrodynamics one of them is distinguished, but it is impossible to detect it.

In order to explain this impossibility of determining the frame of reference in which the ether is resting, G. Fitzgerald in 1888 and Hendrik Antoon Lorentz in 1889 independently assumed, that the length of the body moving towards the ether with velocity v is contracted in the direction of motion; according to Lorentz, in relation $\left(1 - {}^{v^2}\!/_{c^2}\right)^{\frac{1}{2}}$, where $c = 300,000{}^{km}\!/_{s}$ is the velocity of light in vacuum.

Lorentz (see [16]) and Henri Poincaré (see [17]) independently published their theories embracing mechanics and electromagnetics, both based on the assumption of the existence of the ether, on Fitzgerald-Lorentz contraction and on the theory of electron.

Einstein found the solution. In his paper [15] he accepted two principles:

1. All inertial frames of reference are equivivalent as well in the mechanical, as in the electromagnetic respect.

2. The velocity of light in vacuum is always the same, independently of the motion of its source.

From these two principles Einstein proved, in the "mechanical" part of his paper, that the relation between the coordinates of a material point in the considered instant of time in two inertial frames of reference is expressed by Lorentz transformation, he derived the law of relativistic composition of velocities, and formulated relativistic equations of motion of the material point. He noted that his both principles make the concept of the ether unnecessary. (Evolution of Einstein's views on the ether was comprehensively presented by L. Kostro (see [18])).

In the "electromagnetic" part of his paper Einstein did not change Maxwell equations. He investigated transformations of the electric and magnetic vectors, in relation to Lorentz transformation, discussed Doppler and aberration effects, and formulated the electron's equations of motion in the electromagnetic field.

7 The principle of mass and energy equivalence

Basing on the principles of special relativity theory, in a short paper *Ist die Traegheit eines Koerpers von seinem Energieinhalt abhangig?* (Does the inertia of a body depend on the contents of energy in it?) [19] Einstein derived the principle of mass and energy equivalence.

The paper was received by *Annalen* on September 27, 1905, and published on Novebmer 2 of that year.

In this paper Einstein considered a resting body, emitting two equal portions of energy in opposite directions, and observed it from another inertial frame of reference U. By applying the formulae of his paper [15], he calculated the loss of kinetic energy of the observed body from the frame U, and explained it as the loss of the body's mass: *The mass of the body is the measure of its energy contents; when the loss of its energy is equal to L, the loss of its mass is equal to $\frac{L}{9 \cdot 10^{20}}$ if we measure the energy in ergs and the mass in grams.* Later Einstein extended this mechanical principle of the mass and energy equivalence to the phenomena in which the electromagnetic field is present. He did it in his paper *Das Prinzip der Erhaltung der Schwerpunktsbewegung und der Traegheit der Energie* (The principle of conservation of the motion of the center of gravity and inertia of the energy) [20]. This paper was accepted by the editor of *Annalen* on April 17, 1906 and was published on June 26 in the 20$^{\text{th}}$ volume.

8 Consequences of Einstein's paper on special relativity theory

The response to Einstein's paper on electrodynamics of moving bodies was initially very weak. In 1906 only one Max Planck's paper *Das Prinzip der Relativitaet und die Grundlayen der Mechanik* (The principle of relativity and the foundations of mechanics) [21] appeared, in which Planck remarked, in the introduction, that *the principle of relativity introduced recently by H.A. Lorentz, and in still more general formulation by A. Einstein, allows, if testified, for a great simplification of all problems of the electrodynamics of moving bodies.*

Also August Witkowski, professor of experimental physics at Cracow University, became interested in Einstein's paper very early. As Leopold Infeld wrote [22], Witkowski, having read Einstein's paper, said to his assistant Stanisław Loria: ,,New Copernicus is born, read Einstein's paper". Loria paricipated in a congress of physicists in Braeslau. During the congress he inspired the interest of the theoretician Max Born in Einstein's paper. In 1908 Born published his paper *Die traege Masse und das Relativitaetsprinzip* (The inertial mass and the principle of relativity) [23]. In the same year Hermann Minkowski published his paper *Die Grundgleichungen fuer die elektromagnetischen Vergaenge in bewegten Koerpern* (The fundamental equations for electromagentic processes in moving bodies) [24]. Minkowski based mainly on Lorentz' paper, but he remarked that *A. Einstein expressed in most distinct way that this postulate is not an artificial hypothesis, but rather an imposed by phenomena new concept of time.*

Born's paper and the famous Minkowski's lecture *Raum und Zeit* (Space and time) [25] delivered at the eighteenth Congress of German Naturalists and Doctors in 1909 in Koeln contributed in the decisive way to the propagation of the ideas of relativity.

During the next ten years Einstein worked mainly on the creation of the theory of gravitation, which he finally formulated in 1915, calling it the general relativity theory. Basing on it, in 1917 he published the first relativistic (static) model of the Universe. In the next years dynamic models of the Universe were published by S. De Sitter, A Eddington, G. Lemaitre and A. Friedman.

Later Einstein worked many years on the generalisation of the general relativity in order to formulate a theory which would embrace the phenomena of gravitation and electromagnetism. His efforts were not successful. They were initiated too early. The development of physics during the following 50 years which passed from the publication of general relativity theory, resulted in the year 1967 in formulation of the united theory of electromagnetism and weak interaction by S. Glashow, S. Weinberg and A. Salam. The further attemps of the unification of this theory of electroweak interactions with the theory of strong interactions have not been successful. It seems, that the unification of these three interactions with gravitation in one general theory is much more difficult.

9 Nobel Prize for Einstein

Einstein obtained the Nobel Prize in physics in 1921 *for his service to theoretical physics, especially for his discovery of the law of the photoelectric effect* [26]. In this motivation no reference was made to special relativity and to general relativity, which Einstein considered the greatest success of his life. The reason of such a motivation lay in the tendency of the members of the Royal Commission of Nobel Prizes to priviledge and grant experimental work, which could be immediately verified. Lenard's work was of this kind. Therefore Lenard obtained his Nobel Prize in three years after publication of his work. On the contrary, the theoretically calculated derivations of the results of special and general relativity form Newtonian mechanics, known at that time, were very small and difficult for experimental verification. Not earlier than in the thirties and later, phenomena were discovered, in which relativistic effects were significant or prevailing ones.

Einstein did not participate in the celebration of delivering his Nobel Prize, since he was then far from Sweden then. Instead of the Nobel lecture he delivered an article to the Swedish Academy of Sciences, entitled *Fundamental Ideas and Problems of Relativity*, which was published in the edition *Nobel Lectures, Physics 1900–1921* [27].

References

[1] A. Einstein, *AdP*[2] **4**, 543 (1900),

[2] A. Einstein, *AdP* **17**, 132 (1905),

[3] P. Lenard, *AdP* **8**, 149 (1902),

[4] *Nobel Lectures, Physics 1901*, p.99-138, Elsevier, Amsterdam, 1907.

[5] M. Planck, see [4], p. 403-420.

[6] R. Millikan, *Phys.Rev.* **7**, 356, (1916).

[7] *Nobel Lectures, Physics 1922-1941*, p.22, Elzevier, Amsterdam, 1965.

[8] A. Einstein, B. Podolsky, N. Rosen *Phys.Rev.* **47**, 777 (1935).

[9] A. Einstein, *AdP* **17**, 549 (1905).

[10] Ł. Bodaszewski, *Kosmos* **7**, 177 (1982).

[11] M. Smoluchowski, *AdP*, **21**, 750 (1906), see also: *Pisma Mariana Smoluchowskiego*, vol. I, p. 476, 490, Wyd. PAU, Kraków 1924.

[12] A. Einstein, *AdP* **19**, 371 (1906).

[13] See: A. Teske, *Marian Smoluchowski, Leben und Werk* p. 158, PWN, Kraków 1955.

[14] A. Einstein, *AdP* **19**, 289 (1906).

[15] A. Einstein, *AdP* **17**, 891 (1905).

[16] H.A. Lorentz, Proc. Roy. Acad. Sci., Amsterdam **6**, 809 (1904).

[2]AdP – Annalen der Physik

[17] H. Poincaré, *Bull. Sci. Math.* **28**, 302 (1904).

[18] L. Kostro, *Einstein and the rebirth of the ether*, Apeiron, Toronto 2000, 242 p.

[19] A. Einstein, *AdP* **18**, 639 (1905).

[20] A. Einstein, *AdP* **20**, 627 (1906).

[21] M. Planck, *Verh. Der Deutschen phys. Ges.* **8**, 136 (1906).

[22] L. Infeld, *Einstein, jego dzieo i rola w nauce*, p. 66, PWN Warszawa 1956.

[23] M. Born, *AdP* **28**, 571 (1908).

[24] H. Minkowski, in: *Nachricheten von der Koenigl. Ges. zu Goetingen*, phys.-math. Klasse, 1 (1908).

[25] H. Minkowski, *Einstein-Lorentz-Minkowski. Das Relativitaetsprinzip*, Leipzig und Berlin 1913, p. 56-73.

[26] *Nobel Lectures, Physics 1901-1921*, p. 477, Elzevier, Amsterdam 1967.

[27] *ibid,* p. 482–490.