# EINSTEIN AND PHYSICS HUNDRED YEARS AGO*

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In 1905 Albert Einstein published four papers which revolutionized physics. Einstein's ideas concerning energy quanta and electrodynamics of moving bodies were received with scepticism which only very slowly went away in spite of their solid experimental confirmation.

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## 1. Physics around 1900

At the turn of the XX century most scientists regarded physics as an almost completed science which was able to explain all known physical phenomena. It appeared to be a magnificent structure supported by the three mighty pillars: Newton's mechanics, Maxwell's electrodynamics, and thermodynamics.

For the celebrated French chemist Marcellin Berthelot there were no major unsolved problems left in science and the world was without mystery. *Le monde est aujourd'hui sans mystère*— he confidently wrote in 1885 [1]. Albert A. Michelson was of the opinion that "The more important fundamental laws and facts of physical science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote .... Our future discoveries must be looked for in the sixth place of decimals" [2]. Physics was not only effective but also perfect and beautiful. Henri Poincaré maintained that "The theory of light based on the works of Fresnel and his successors is the most perfect of all the theories of physics" [3].

On April 27, 1900 Lord Kelvin delivered famous lecture entitled *Nineteenth Century Clouds over the Dynamical Theory of Heat*. The expanded

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version of this lecture was published the following year [4]. In the introduction we find the statement often quoted as a quintessence of the *fin-de-siècle* confidence in classical physics:

"The beauty and clearness of the dynamical theory, which asserts heat and light to be modes of motion, is at present obscured by two clouds. I. The first came into existence with the undulatory theory of light, and was dealt with by Fresnel and Dr. Thomas Young; it involved the question, how could the earth move through an elastic solid, such as essentially is the luminiferous ether? II. The second is the Maxwell–Boltzmann doctrine regarding the partition of energy."

The original documents of that period, *e.g.* the texts of the First International Congress of Physics held in Paris, 6–12 August, 1900, leave little doubt that the then active physicists were mostly satisfied with classical physics and saw little need for "new" physics [5]. Only later we learned that it required special relativity and quantum theory to blow away Kelvin's clouds.

Albert Einstein was born in 1879. At the end of July, 1900, he completed studies at the Swiss Polytechnical School (since 1911 called ETH) in Zurich and obtained the diploma which entitled him to teach in high schools. Unable to obtain a position as assistant at the Polytechnical School he looked for employment elsewhere. After several temporary teaching positions in various institutions, he finally found appointment in 1902 in the patent office in Bern. There he was formally isolated from university physics but continued to study physics literature and pursue critical analysis of the foundations of classical physics. In 1905 Einstein published in the *Annalen der Physik* four papers [6–9] which revolutionized physics.

## 2. The energy quantum paper

The first Einstein's paper, entitled *On a Heuristic Point of View Concerning the Production and Transformation of Light* was submitted on March 17. It starts with a clear exposition of the problem which motivated Einstein to look for a solution that would satisfy his pursuit of simplicity in physical theory [10].

"A profound difference exists between the theoretical concepts that physicists have formed about gases and other ponderable bodies, and Maxwell's theory of electromagnetic phenomena in so-called empty space. While we consider the state of a body to be completely determined by the positions and velocities of an indeed very large yet finite number of atoms and electrons, we make use of continuous spatial functions to determine the electromagnetic state of a volume of space, so that a finite number of quantities cannot be considered as sufficient for the complete determination of the electromagnetic state of space. According to Maxwell's theory, energy is considered to be a continuous spatial function for all purely electromagnetic phenomena, hence also for light, whereas according to the present view of physicists, the energy of a ponderable body should be represented as a sum over the atoms and electrons."

Einstein was convinced that this difference between theoretical concepts can be removed. He continued:

"Indeed, it seems to me that the observations of 'black-body radiation', photoluminescence, production of cathode rays by ultraviolet light, and other related phenomena associated with the emission or transformation of light appear more readily understood if one assumes that the energy of light is discontinuously distributed in space. According with the assumption considered here, in the propagation of a light ray emitted from a point source, the energy is not distributed continuously over ever-increasing volumes of space, but consists of a finite number of energy quanta localized at points of space that move without dividing, and can be absorbed or generated only as complete units . . . "

Einstein knew that Wien's law for "black body radiation" was valid only for high-frequency limit, but he used it nevertheless to calculate the difference in entropy $S$ to be expected in the radiation within the frequency range between $\nu$ and $\nu + d\nu$ if the occupied volume in the cavity changed from $V_0$ to $V$. He obtained $S - S_0 = \frac{E}{\beta\nu}\ln(V/V_0)$, where $E$ is the total energy in the sample. Then, from Boltzmann's formula for the entropy of a gas he calculated the change in entropy as a function of the probability $W$ of the state: $S - S_0 = \frac{R}{N}\ln W$, where $R$ denotes the universal gas constant, and $N$ — the Avogadro number. Noticing the obvious similarity of the two formulas Einstein remarked that "the entropy of a monochromatic radiation of a sufficiently low density follows the same laws of variation with volume as does the entropy of an ideal gas . . . ."

After further calculations Einstein obtained the now famous equation for the photoelectric effect: $\Pi\varepsilon = \frac{R}{N}\beta\nu - P$, where $\Pi$ is the positive potential, $\varepsilon$ denotes the charge of the electron, $\nu$ — the frequency of the incident light, and $P$ is the work performed by the electron before leaving the cathode. In derivation of the above equation Einstein assumed that the entire energy of the incident quantum is transferred to the electron in the metal. Today we write this formula in a simplified form $E = h\nu - P$.

"If the formula derived is correct, then $\Pi$, when plotted in Cartesian coordinates as a function of the frequency of the incident light, must give a straight line whose slope is independent of the nature of the substance under study. As far as I can tell, this conception of the photoelectric effect does not contradict its properties as observed by Mr. Lenard. If each energy quantum of the incident light transmits its energy to electrons, independently of all others, then the velocity distribution of the electrons, *i.e.*, the nature of cathode rays produced, will be independent of the intensity of the incident light; on the other hand, under otherwise identical circumstances, the number of electrons leaving the body will be proportional to the intensity of the incident light" [10].

Now, it is interesting that Einstein did not use Planck's constant $h$, although it was proposed five years earlier, but used instead the combination $\frac{R}{N}\beta$, as if he wanted to stress that his reasoning was independent of Planck's. It is also interesting that Einstein at that time did not exclude the possibility that electrons can absorb only parts of the energy of light quanta, in which case the above equation for the photoelectric effect would become an inequality $\Pi\varepsilon \leq \frac{R}{N}\beta\nu - P$.

## 3. The reception of the energy quantum hypothesis

By 1905 there were about 200 published papers on the photoelectric effect, many of them incorrect or irrelevant. Einstein cited only one of them, the 1902 *Annalen der Physik* paper by Philipp Lenard [11]. Einstein showed exceptional intuition in singling out this particular paper, because Lenard's experiments were performed with particular care and skill. Lenard reported that the velocity of the emitted electrons did not depend on the intensity of the incident radiation. He did not, as is sometimes claimed, demonstrate that the velocity of electrons varied with light frequency, but showed only that it depended on the type of light used (arc light or spark light).

According to classical physics the energy of the electromagnetic wave depends on its amplitude. Thus, if this energy was directly transferred to the electrons, their velocity should be proportional to the intensity of light. The experiments by Lenard showed that it was not so. One can sometimes read in the textbooks that classical physics was therefore unable to provide an explanation for the photoelectric effect. It is not true. In fact, there were several classical theories of the photoeffect. Lenard himself initiated the "trigger hypothesis" when he wrote [ [11] p. 170] that "the initial velocities of the emitted quanta [*this was the term for photoelectrons used by Lenard*] do not originate from light energy at all, but from the violent motions existing already before the illumination within the interior of the atoms; thus the resonance motions [of the electrons stimulated by the incident radiation] only play the role of a mechanism for the release [of electrons]." Other theories were proposed by renowned physicists such as Joseph John Thomson [12,13], Arnold Sommerfeld [14] and Owen W. Richardson [15,16]. From consideration of an electron gas inside the metal Richardson [16] even derived a linear relation between the kinetic energy of the photoelectrons and the frequency of the incident light which was formally identical to Einstein's equation. "It appears therefore that the confirmation of the above equation … by experiment would not necessarily involve the acceptance of the unitary theory of light" — he concluded [16]. One may find detailed description of the classical theories of the photoelectric effect in a superb book by Roger H. Stuewer [17].

The experimental issue was by no means settled. The proportionality of the number of photoelectrons to the intensity of light, found by Lenard, was questioned by other experimenters [18]. The linear dependence of the electron energy on the frequency of light predicted by Einstein was even harder to establish. For several years papers were published with conflicting experimental results. In 1907 Emil Ladenburg found [19] that the velocity itself, and not the square of the velocity is proportional to the frequency of light. In 1911 Frederick Lindemann advocated $E \sim \nu^{2/3}$ and claimed that Ladenburg's results could also be fitted with this formula [20]. Jakob Kunz [21] at first believed that his measurements verified Einstein's formula, but later, on the basis of a theory of his own, proposed a relation according to which the electron energy increased proportionally to $\nu^2$. In fact, his results, as well as those of his pupil David Cornelius [22], could be equally well represented by either formula. Karl T. Compton and Owen Richardson [23–25] performed numerous measurements and argued that they confirmed the linear "Einstein–Richardson relation" between electron energy and light frequency. They criticised Cornelius and pointed out that his poor results corresponded even better to a proportionality $E \sim \nu^3$. Arthur L. Hughes [26] was of the opinion that his experimental points confirm linear energy–frequency relation.

In 1913 Robert Pohl and Peter Pringsheim wrote a review paper [27], in which they analysed the results of all experiments done after 1905. They pointed out that because of rather restricted range of frequencies over which the Compton–Richardson experiments were done, the results could be reasonably well fitted with a number of other relationships, including a logarithmic one: $E = k \log \nu - h\nu_0$.

The only physicist who supported Einstein in these years was Johannes Stark (born 1874). In 1909 he first wrote the expression for the momentum of a light quantum explicitly as $h\nu/c$ [28]. Hendrik Lorentz was sceptical. His speculations on light quanta show that he imagined a light quantum to be sort of a large ball of light. He argued that the interference experiments of Lummer and Gehrcke, which involved path differences up to roughly 80 cm, proved that distance represented a lower limit on the longitudinal extension of quanta. The then largest telescope on Mt. Wilson had a mirror of 150 cm diameter and it — Lorentz argued — represented a lower limit on the lateral extension of quanta. How could a quantum this monstrously large pass through the pupil of an eye without being subdivided? — asked Lorentz [29].

Max Planck, who started the quantum revolution in physics, did not believe in energy quanta. In the talk at the 1911 Solvay Council he declared that: "If one considers the complete experimental confirmation which Maxwell's electrodynamic theory obtained by means of the most delicate interference phenomena, and if one considers the extraordinary difficulties which its abandonment would entail for the entire theory of electric and magnetic phenomena, then one senses a certain repugnance in ruining its very fundamentals. For this reason, we shall leave aside the hypothesis of light quanta, especially since it is still quite early in the development of this notion" [30].

Two years later, when Einstein was proposed for membership in the Prussian Academy of Sciences, the nominators, Max Planck, Walther Nernst, Heinrich Rubens and Emil Warburg, praised Einstein, but they also wrote: "That he sometimes has 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" [31].

Meanwhile, Robert A. Millikan had already worked on the photoelectric effect for several years. In 1916 he published a long paper giving all the results of his careful experiment. His results confirmed Einstein's linear equation with great precision. Millikan, however, remained a strong opponent of the light quantum theory. "It was in 1905 that Einstein made the first coupling of photo effects with any form of quantum theory by bringing forward the bold, not to say, the reckless, hypothesis of an electromagnetic light corpuscle of energy $h\nu$, which energy was transferred upon absorption to an electron. This hypothesis may well be called reckless first because an electromagnetic disturbance which remains localized in space seems a violation of the very conception of an electromagnetic disturbance, and second because it flies in the face of the thoroughly established facts of interference ... Despite then the apparent complete success of the Einstein equation, the physical theory of which it was designed to be the symbolic expression is found so untenable that Einstein himself, I believe, no longer holds to it" [32].

In November 1922 Einstein was awarded the 1921 Nobel Prize in Physics for "his services to theoretical physics, and especially for his discovery of the laws of the photoelectric effect". It did not, however, end the attacks on the concept of light quanta. In 1925 James Jeans wrote that

" ... a short step leads directly to the hypothesis of 'light-quanta', according to which all radiation consists of indivisible packets or 'atoms' of monochromatic light, each of which travels through space like a bullet from a rifle until it hits a material target by which it is completely absorbed. This view was put forward as a working hypothesis by Einstein in 1905, and at once enabled him to formulate the true law of photo-electric action. In spite of this success it appears fairly certain that the view must be regarded merely as a working hypothesis and not as a literal expression of actual fact. Against the supposition that radiation actually travels in indivisible quanta must be set practically all the evidence of the undulatory theory of light, and, in particular, that of the phenomena of diffraction and interference ... The general opinion of physicists seems to be that the theory cannot be regarded as an expression of physical reality" [33].

## 4. The Brownian motion paper

The second paper [7] which Einstein submitted to the *Annalen der Physik* on May 11, will not be discussed here. It is known that the problem of Brownian motion would have been anyway solved soon even without Einstein, because Marian Smoluchowski independently worked on this phenomenon. In fact he had finished calculations earlier but was slow to prepare the report. Einstein's paper stimulated him to finish the paper, so that the publication with his independent solution appeared only few months later [34]. Let us note only that the Einstein–Smoluchowski equation for Brownian motion provided the decisive quantitative explanation of this phenomenon and played an important role in the acceptance of the kinetic theory of matter.

## 5. The special relativity paper

Einstein's paper on electrodynamics of moving bodies [8] was submitted to the *Annalen der Physik* on June 30. Its style is similar to the first paper [6] in that its motivation: to remove an apparent asymmetry in explaining identical phenomena, is again clearly stated in the introduction.

"It is well known that Maxwell's electrodynamics — as usually understood at present — when applied to moving bodies, leads to asymmetries that do not seem to be inherent in the phenomena. Take, for example, the electrodynamic interaction between a magnet and a conductor. The observable phenomenon here depends only on the relative motion of conductor and magnet, whereas the customary view draws a sharp distinction between the two cases, in which either the one or the other of the two bodies is in motion."

"For if the magnet is in motion and the conductor is at rest, an electric field with a definite energy value results in the vicinity of the magnet that produces a current wherever parts of the conductor are located. But if the magnet is at rest while the conductor is moving, no electric field results in the vicinity of the magnet, but rather an electromotive force in the conductor, to which no energy per se corresponds, but which, assuming an equality of relative motion in the two cases, gives rise to electric currents of the same magnitude and the same course as those produced by the electric forces in the former case."

"Examples of this sort, together with the unsuccessful attempts to detect a motion of the earth relative to the 'light medium', lead to the conjecture that not only the phenomena of mechanics but also those of electrodynamics have no properties that correspond to the concept of absolute rest ...

We shall raise this conjecture (whose content will hereafter be called 'the principle of relativity') to the status of a postulate and shall also introduce another postulate, which is only seemingly incompatible with it, namely that light always propagates with a definite velocity $V$ that is independent of the state of motion of the emitting body. These two postulates suffice for the attainment of a simple and consistent electrodynamics of moving bodies based on Maxwell's theory for bodies at rest" [35].

Einstein's paper consisted of two parts. In the first, kinematic, Einstein defined simultaneity of events and relativity of lengths and times, and he derived the transformation equations ("Lorentz transformation") for coordinates and time in systems in uniform translational motion. In the second, electrodynamic, he applied his kinematic results to the solution of several problems of optics and electrodynamics of moving bodies.

The fourth paper [9], submitted on September 27, was very brief but contained announcement of an important discovery: "If a body emits the energy $L$ in the form of radiation, its mass decreases by $L/V^2$". That was the original form of the most famous equation of physics: $E = mc^2$.

### 6. The reception of the special relativity theory

Already before Einstein several physicists published results which were formally similar or identical to those which he presented in his paper on electrodynamics of moving bodies. One cannot properly assess the reception of Einstein's ideas without summarizing those other results.

Woldemar Voigt of Göttingen is sometimes erroneously presented as discoverer of the Lorentz transformation. He studied propagation of deformation waves in an isotropic and homogeneous elastic medium. In 1887 he found [36] that the results are invariant under the transformation

$$x'_1 = x_1 - vt\,, \qquad y'_1 = y_1(1 - v^2/\omega^2)\,,$$
$$z'_1 = z_1(1 - v^2/\omega^2)\,, \qquad t' = t - vx_1/\omega^2\,,$$

where $\omega$ is the phase velocity. It is easily seen that Voigt's formulae are different from the Lorentz transformation. A good assessment of Voigt's work may be found in [37].

By 1892 Hendrik Lorentz developed a theory of electromagnetic phenomena in moving bodies. In order to explain the result of the Michelson–Morley experiment he assumed that in motion through the elastic immobile ether the dimension of a body in the direction of motion is contracted by a factor $1 - 2v^2/c^2$. His calculations were done to the first order in $v/c$. In his subsequent paper in 1895 the contraction factor was changed to $(1 - v^2/c^2)^{1/2}$. Even earlier George FitzGerald independently conceived the idea of such a contraction. It was considered to be real and resulting from the properties of molecular forces (hence the name FitzGerald–Lorentz contraction). In 1899 Lorentz analysed also a transformation of time scale. He introduced the concept of "local time", which was thought to be only a mathematical tool with no connection with real time. It was found that in the transformation for dielectric displacement and magnetic force vectors from the rest system to a moving system, the same equations of the electron theory will hold in the moving system if the "local time" is used for the time in that system. An excellent résumé of successive versions of Lorentz's theory by Kenneth Schaffner may be found in [38].

First in 1897, and then in 1900 in a book *Aether and Matter* [39], Joseph Larmor announced his electron theory of matter. He used "Lorentz transformation" for $x, y, z, t$ and derived the FitzGerald–Lorentz contraction. He also gave transformations of electric and magnetic fields and stressed that the results are exact only to order $v^2/c^2$. He did not pursue his analysis to include all orders of $v/c$. A detailed assessment of Larmor's work may be found in [37].

In 1902 Lord Rayleigh pointed out that the Lorentz–Fiztgerald contraction should cause a strain in moving bodies and result in double refraction of the order of $v^2/c^2$. He tested several liquids and solids but did not find a measurable effect (it was less than 1 percent of the calculated effect) [40]. The experiment repeated with increased accuracy in 1904 by DeWitt Brace [41] also gave null result. In 1903 Frederick Trouton and H.R. Noble placed a charged condenser at an angle with the direction of the earth's motion through the ether and attempted to detect a torque which the condenser should experience to align it with that direction. No measurable torque was detected [42]. Lorentz's old theory could not account for these results. His answer was the famous paper [43] published in 1904. Lorentz developed his theory to be able to apply it to second and higher orders of $v/c$. He proved the invariance of Maxwell's equations with respect to postulated transformation (which we now call, after Poincaré, the Lorentz transformation). He also developed a new hypothesis concerning the electron; we shall come to it later.

We must also mention another development that took place in the years preceeding 1905. In 1900 Wilhelm Wien published a paper *On the Possibility of an Electromagnetic Foundation of Mechanics* [44], in which he postulated that all mass was of electromagnetic origin. It is usually treated as the beginning of research toward the electromagnetic world picture.

Max Abraham from Göttingen became one of the chief propagators of a program of replacing the laws of newtonian mechanics by the laws of Maxwell's electrodynamics, which were to be recognized as fundamental laws of physics. The mass of the electron, believed to be of electromagnetic origin, was predicted to increase with its velocity through the ether. Lorentz in 1899 had already speculated on a possible change of electron's mass with its velocity. Abraham assumed that electron's charge was distributed uniformly over the surface of a rigid sphere and derived a formula for the change of its mass [45, 46]. Writing the mass $m$ as a function of velocity $\beta = v/c$ in the form $m = m_0 \Psi(\beta)$, where $m_0$ is the rest mass, in Abraham's theory we had

$$\Psi(\beta) = \frac{3}{4\beta^2}\left[\left(\frac{1+\beta^2}{2\beta}\right)\ln\left(\frac{1+\beta}{1-\beta}\right) - 1\right].$$

In 1901 Abraham's colleague from Göttingen, Walter Kaufmann, began measurements of the $e/m$ ratio of beta rays from radium chloride. The mass of electrons was indeed found [47, 48] to depend on their velocity according to Abraham's formula. It was acclaimed as a triumph of the electromagnetic world picture.

In September 1904 a week-long Congress of Arts and Science was held in St. Louis in conjunction with the Universal Exposition. The talks delivered during the Congress by leading physicists provided an excellent panorama of physics of that time. A selection of papers from the original eight volumes of the Proceedings of the Congress was published recently [49].

Carl Barus in the talk on the progress of physics in the nineteenth century concluded that [50]: "It is now confidently affirmed that the mass of the electron is wholly of the nature of electromagnetic inertia, and hence, as Abraham (1902), utilizing Kaufmann's data (1902) on the increase of electromagnetic mass with the velocity of the corpuscule, has shown, the Lagrangian equations of motion may be recast in an electromagnetic form."

The rigid electron model of Abraham excited criticism. Hermann Minkowski remarked jokingly that to introduce a rigid electron into the Maxwell theory is like going to a concert with cotton in one's ears. Two other models of the electron were proposed soon. In his 1904 paper [43] Lorentz assumed that the charge of the electron is distributed uniformly over the surface of a sphere, which undergoes deformation in motion through the ether. Alfred Bucherer in 1904 [51] and independently Paul Langevin [52] preferred electron's charge to be distributed uniformly over the surface of a sphere which is deformed in motion through the ether, such that its volume remains constant.

The electron mass as function of its velocity in Lorentz' model was $\Psi(\beta) = (1-\beta^2)^{-1/2}$, whereas in Bucherer's model it was $\Psi(\beta) = \left(1-\beta^2\right)^{-1/3}$.

In his paper on electrodynamics of moving bodies [8] Einstein also derived a formula for the change of the electron's mass with its velocity. It was formally identical to Lorentz's formula. It was a coincidence because Lorentz's and Einstein's were two different theories. Einstein's theory did not depend in any way on the existence of electrons. Nevertheless, until about 1910 Einstein's results in the relativity paper [8] were considered to be a generalization of Lorentz's theory of the electron [43], hence the name "Lorentz–Einstein theory".

Not only the mass–velocity formula but certain other results in the Einstein's paper were mathematically, but not physically, equivalent to Lorentz's. Before presenting a detailed comparison of the two theories let us concentrate on the experimental verification of the predictions for electron mass variation.

The differences in the mass–velocity relations in the three models of the electron are better seen when we compare the first terms of the expansion of $\Psi(\beta)$. We have then

$$\Psi(\beta) \approx 1 + \tfrac{2}{5}\beta^2 + \tfrac{9}{35}\beta^4 + \ldots \quad \text{Abraham's model}$$

$$\Psi(\beta) \approx 1 + \tfrac{1}{2}\beta^2 + \tfrac{3}{8}\beta^4 + \ldots \quad \text{Lorentz model, Einstein special relativity theory}$$

$$\Psi(\beta) \approx 1 + \tfrac{1}{3}\beta^2 + \tfrac{2}{9}\beta^4 + \ldots \quad \text{Bucherer, Langevin}$$

It would seem from Fig. 1 that it was easy to discriminate between the three models. In reality it was not so. The experiments by Kaufmann and later by others involved measurements of the charge to mass $(e/m)$ ratio of beta rays from their deflection in parallel electric and magnetic fields. However, the velocity of the electrons was not precisely known and also, at that time, the electron's charge $e$ was known with rather large error. In reality, then, the rather uncertain procedure of deriving $m(v)$ values involved fitting the observed deflections to the calculations based on the theory. An excellent review of various experiments on the mass–velocity relation is given in [53].

Thus, Paul Langevin in his talk on the physics of electrons at the St. Louis Congress in 1904 discussed the three models of the electron and concluded that [54]: "The experimental points … given by Kaufmann … correspond equally well with the three theoretical curves." (see Fig. 2).

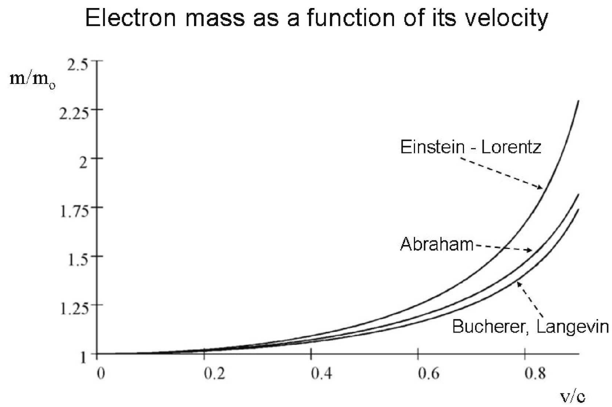


Fig. 1. The dependence of the mass $m$ of the electron on its velocity according to the three models of the electron by Abraham [45], Bucherer [51] and Langevin [52], and Lorentz [43]. Einstein's formula given in the special relativity paper [8] is formally identical to that of Lorentz.

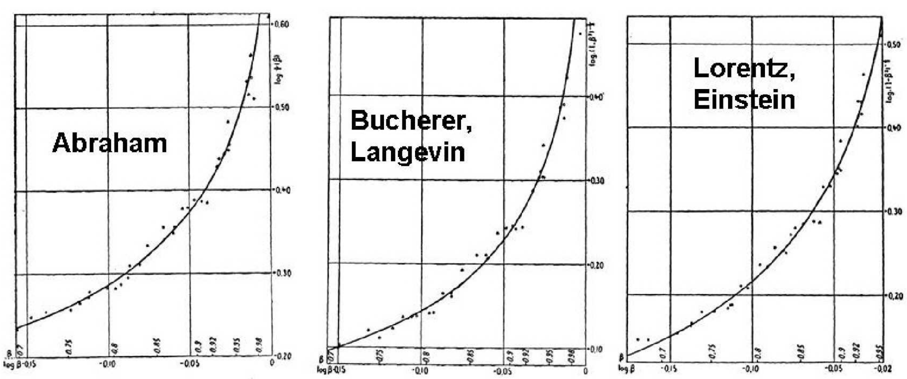


Fig. 2. The results of the reanalysis by Paul Langevin of Kaufmann's measurements of the electron mass at various velocities. In the three parts of the figure the experimental points are the same but the curves were calculated according to the three models of the electron (adapted from Langevin's talk at the 1904 St. Louis Congress [54].

On the other hand, Kaufmann continued his measurements [55–57] and insisted that the results agree with the prediction of the Abraham's model. "The results … speak against the correctness of Lorentz's, and also consequently of Einstein's, fundamental hypothesis. If one considers this hypothesis as thereby refuted, then the attempt to base the whole of physics, including electrodynamics and optics, upon the principle of relative motion is also a failure … A decision between the theories of Abraham and of

Bucherer is meanwhile impossible and appears not attainable by observations of the type described above ... [58]" — Einstein remained unmoved by these remarks. He reanalysed Kaufmann's data and was convinced that they were not in contradiction with the mass–velocity relation resulting from the relativity theory.

In 1907 A. Bestelmeyer sent the cathode rays through crossed electric and magnetic fields acting as velocity selector and then analysed them by magnetic field alone. The value of $e/m_0$ was adjusted to give the best fit to each of the three theories. One should remember that the value of $e$ was still known with considerable uncertainty. The results [59] could not discriminate between the three theories. In 1908 Bucherer used similar method to measure beta particles from radium chloride source. He abandoned his own model and decided that the data agree a little better with the Lorentz–Einstein formula than with Abraham's [60]. The results of Hupka [61] were of little help in solving the controversy. Finally, the precise experiments of Neumann in 1914 definitely proved that the Lorentz–Einstein formula provided the best fit to the data [62]. This conclusion was confirmed by Guye and Lavanchy [63]. At that time many physicists already knew that in spite of the same mathematical form of the mass–velocity relation, the theories of Lorentz and Einstein were quite different.

## 7. Einstein, Lorentz, and Poincaré

In 1953 Edmund T. Whittaker published a second volume of his book *A History of the Theories of Aether and Electricity*, covering the period 1900–1926 [64]. In Chapter 2, entitled 'The relativity theory of Poincaré and Lorentz', we find the following statement:

"In the autumn of the same year, in the same volume of the Annalen der Physik as his paper on the Brownian motion, Einstein published a paper which set forth the relativity theory of Poincaré and Lorentz with some amplifications, and which attracted much attention."

This unjust statement, depreciating Einstein's role in relativity theory, took many physicists by surprise. Abraham Pais commented that it "shows how well the author's lack of physical insight matches his ignorance" [65]. Indeed, Whittaker's opinion could be simply ignored if it were not for the fact that the first volume of his *History of the Theories of Aether and Electricity* gave an excellent account of earlier events to the end of the nineteenth century. For that reason Whittaker's largely distorted presentation of the origins of special relativity raised questions among the readers about the priorities in the discovery in that theory.

Nowadays, in the age of internet, information noise is greater than ever. The number of amateurish texts which propagate distorted accounts of

Einstein's accomplishments over the World Wide Web has increased significantly on the occasion of the World Year of Physics. In some papers Einstein is even called a plagiarist. Thus, it seems proper to conclude this presentation with a factual summary of the works of Einstein, Lorentz, and Poincaré.

As mentioned above, certain results in the Einstein's paper on electrodynamics of moving bodies were mathematically, but not physically, equivalent to Lorentz's paper of 1904. However, Lorentz's and Einstein's are two different theories.

Gerald Holton [66] analysed Lorentz's paper of 1904 and identified eleven *ad hoc* hypotheses which it contained. These were: restriction to small velocities, $v \ll c$; postulation *a priori* of the [Lorentz] transformation equations; assumption of a stationary ether; assumption that the stationary electron is spherical; that its charge is uniformly distributed; that all mass is electromagnetic; that the moving electron is contracted by precisely $(1-v^2/c^2)^{1/2}$; that forces between uncharged and charged particles have the same transformation properties as electrostatic forces in the electrostatic system; that all charges in atoms are in a certain number of "electrons"; that each of these "electrons" is acted on only by other "electrons" of the same atom; and that atoms in motion as a whole deform as electrons do.

In contrast to that impressive list Einstein used only two postulates: 1. The velocity of light in empty space $c$ is the same in all inertial frames independently of the relative motion of an observer and a source, and 2. The principle of relativity, that the laws of physics are identical in all inertial frames.

In addition Einstein made use of the postulate of isotropy and homogeneity of space and of logical postulates concerning synchronization of clocks (if the clock at A runs synchronously with the clock at B, then the clock at B runs synchronously with the clock at A, *etc.*).

On the basis of these two postulates Einstein *derived* [Lorentz] transformation equations for the coordinates, time and fields, and also derived the formula for addition of velocities, and the formula for the Lorentz force (which Lorentz only postulated in 1895). Einstein's theory did not depend in any way on the existence of electrons.

In Lorentz's theory only one reference frame is privileged, the one of stationary ether. In this frame the rods have the largest length and, when in motion, they become shorter because of the contraction, which is a real phenomenon, resulting from the properties of molecular forces. The inverse transformation is not reciprocal. Systems which are at rest in the ether are spatially dilated in comparison with the moving system. In the relativity theory of Einstein length contraction is a kinematic effect. It is reciprocal as other effects of kinematic origin.

In 1927 Lorentz said [67]: "I introduced the conception of local time ... but I never thought that this had anything to do with real time. This real time for me was still represented by the older classical notion of absolute time ... There existed for me only one true time. I considered my time transformation only as a heuristic working hypothesis. So, the theory of relativity is really solely Einstein's work."

A very comprehensive comparison of Lorentz's and Einstein's work has been provided by Stanley Goldberg [68].

Henri Poincaré also believed in the existence of the privileged system, that of the immobile ether. It is clearly documented by what he said in the talk at the 1904 St. Louis Congress of Arts and Science [69]:

"The principle of relativity, according to which the laws of physical phenomena should be the same, whether for an observer fixed, or for an observer carried along in a uniform movement of translation; so that we have not and could not have any means of discerning whether or not we are carried along in such a motion ...

The most remarkable example of this new mathematical physics is, beyond contradiction, Maxwell's electro-magnetic theory of light.

We know nothing of the ether, how its molecules are disposed, whether they attract or repel each other; but we know that this medium transmits at the same time the optical perturbations; we know that this transmission should be made conformably to the general principles of mechanics, and that suffices us for the establishment of the equations of the electromagnetic field .... .

Perhaps, likewise, we should construct a whole new mechanics, of which we only succeed in catching a glimpse, where inertia increasing with the velocity, the velocity of light would become an impassable limit. The ordinary mechanics, more simple, would remain a first approximation, since it would be true for velocities not too great, so that we should still find the old dynamics under the new."

In that talk Poincaré for the first time used the name "principle of relativity", but he was still discussing ether and "fixed observer". In June 1905 Poincaré published a paper on the dynamics of the electron [70]. It was largely a discussion of the 1904 paper by Lorentz, to which certain corrections were proposed. Among other things Poincaré suggested the name "Lorentz transformation" for the set of formulas postulated by Lorentz. He also hypothesized that the deformable and compressible electron may be subject to a sort of constant external pressure proportional to the volume. This, he wrote, may be a possible explanation of electron's contraction. Thus, there could be no doubt that Poincaré, despite his insistence on the principle of relativity, was still on the same old track of ether and deformable electrons.

In 1909 Poincaré lectured in Göttingen on *La Mécanique Nouvelle*. He based this new mechanics on three hypotheses:

1. The velocity of light in empty space is a limit which cannot be crossed by any material body.

2. The laws of physics are the same in all inertial frames.

3. A body in translatory motion undergoes a deformation in the direction of motion. Commenting on the third postulate he added: "However strange this hypothesis may seem, we must admit that this third hypothesis is very well confirmed."

Thus, four years after Einstein's paper, Poincaré still did not understand that length contraction is a consequence of the two Einstein's postulates. One may add that in his presentation Poincaré did not mention Einstein at all. The readers interested in a more detailed analysis of the contributions of Poincaré will find it in Ref. [71] and [72].

Einstein met Poincaré at the Solvay Council in 1911. He later wrote to his friend Heinrich Zangger [73]: "Poincaré was simply generally antipathetic (in regard to relativity theory) and showed little understanding for the situation despite all his sharp wit."

To conclude: Lorentz (b. 1853), Poincaré (b. 1854) and other eminent physicists realized the need of a new physics. They have discovered some important facts, but were convinced that ether must exist. That's why their results had little connection with the revolutionary ideas of Einstein who belonged to a younger generation. It is worth adding that many physicists could appreciate the real significance of the innovation proposed by Einstein after they became acquainted with a brilliant reinterpretation of relativistic kinematics in terms of four-dimensional space-time by Hermann Minkowski [74].

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