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Hazy Spots on Photographic Plates: On the Measurement of the Velocity-Dependency of the Electron's Mass

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ABSTRACT

In this article, different experimental attempts to measure the velocity-dependency of the electron's mass will be discussed. These experiments were carried out between 1901 and 1916 by Walter Kaufmann, Alfred Bucherer, Günther Neumann, and Charles-Eugène Guye together with Charles Lavanchy. They all attempted to capture this effect on photographic plates, such that it could then be measured afterward as precisely as the plates allowed for. It will be argued that two different approaches to the production of precise photographic plates can be distinguished: one that conceptualized precision in terms of qualitative plates, and one that attempted to achieve it through quantity. In the final part of the article, it will then be argued that these two approaches were shaped both by the specific radiating materials at hand as well as by the intellectual context in which the scientists involved were working.

KEY WORDS: electron experiments, velocity-dependency mass, photographic plates, theory of relativity, precision measurement, replications

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INTRODUCTION

In 1906, Walter Kaufmann carried out experiments to measure as precisely as possible the dependency of the electron's mass on its velocity. The results, he

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The following abbreviations are used: AdP, Annalen der Physik; NGWG, Nachrichten von der Gesellschaft der Wissenschaften zu Göttingen, Mathematisch Physikalische Klasse; PZ, Physikalische Zeitschrift; SHPMP, Studies in History and Philosophy of Modern Physics; PM, The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science; VDPS, Verhandlungen der Deutschen Physikalischen Gesellschaft

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claimed, were quite significant as they clearly problematized a theory that had made its appearance only a year earlier, namely, Albert Einstein's 1905 theory of relativity. As Kaufmann put it, his measurements "clearly decide against the correctness of Lorentz's and hence also Einstein's theory; if one considers these as refuted, then the attempt to base the whole of physics, including electrodynamics and optics, on the principle of relative motion has to be considered a failure as well."[1]

Kaufmann's experiments have been discussed extensively in their role as the first experimental test of the theory of relativity.[2] Less attention has been paid, however, to how the precision required to make such claims was believed to be attainable. This was by means of photographic plates which, according to Kaufmann, were so clear and sharp that "on each plate produced one obtains a whole series of observations, from which one can directly read off the dependency between *e/m* and *v*" (with *e* denoting the electron's charge, *m* its mass, and *v* its velocity).[3]

While many were impressed by Kaufmann's results, not all were convinced. In 1908, Gilbert N. Lewis stated that "it seems almost incredible that measurements of the minute displacement of a somewhat hazy spot on a photographic plate, could have been determined with the precision claimed."[4] And a few decades later, C. T. Zahn and A. H. Spees argued that their calculations and measurements showed "how fallacious it may be to assume that the mere existence of fairly sharp photographic lines is a good criterion for the proper functioning [of the experiment]."[5]

Studying the production and evaluation of these photographic plates can not only teach us more about the context in which the theory of relativity was

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[1] Walter Kaufmann, "Über die Konstitution des Elektrons," *AdP* 324 (1906): 487–553, on 534.

[2] Arthur I. Miller, *Albert Einstein's Special Theory of Relativity: Emergence (1905) and Early Interpretation (1905–1911)* (Reading, PA: Addison-Wesley Publishing Company, 1981); James T. Cushing, "Electromagnetic Mass, Relativity, and the Kaufmann Experiments," *American Journal of Physics* 49 (1981): 1133–49; Richard Staley, *Einstein's Generation: The Origins of the Relativity Revolution* (Chicago: University of Chicago Press, 2008); Michel Janssen, "Drawing the Line between Kinematics and Dynamics in Special Relativity," *SHPMP* 40 (2009): 26–52; Jan Potters, "Heuristics versus Norms: On the Relativistic Responses to the Kaufmann Experiments," *SHPMP* 66 (2019): 69–89; Marco Giovanelli, "Like Thermodynamics before Boltzmann: On the Emergence of Einstein's Distinction between Constructive and Principle theories," *SHPMP* 71 (2020): 118–57.

[3] Walter Kaufmann, "Die magnetische und electrische Ablenkbarkeit der Becquerelstrahlen und die scheinbare Masse der Elektronen," *NGWG* (1901): 143–55, on 144–45.

[4] Gilbert N. Lewis, "A Revision of the Fundamental Laws of Matter and Energy," *PM* 6 (1908): 705–17, on 713.

[5] C. T. Zahn and A. H. Spees, "A Critical Analysis of the Classical Experiments on the Relativistic Variation of Electron Mass," *Physical Review* 53 (1938): 511–21, on 518.

first received, however. It can equally well contribute to a better understanding of scientific photography and scientific visualization cultures. The reason for this is that their production essentially relied on radioactive phenomena, which, as Kelley Wilder has argued in her work on Henri Becquerel's photographic plates (which were produced at around the same time), was a very peculiar photographic material:

> Visualizations of radioactivity were by their very nature highly constructed in a way that no scientific photograph had so far been, because the radioactivity needed to be constrained and formed into a shape in order for it to appear at all on the photographic plates. This shape was constrained not only by Becquerel's imagination, but by the nature of photographic and radioactive materials.[6]

In line with Wilder's discussion of Becquerel's style of scientific photography,[7] the current article will discuss four experiments—Kaufmann's original ones and three replication attempts—and argue that two visualization styles can be distinguished: one that conceptualized precision in terms of qualitative plates, and one that attempted to achieve precision through quantity. It will then be argued that these styles were shaped both by the specific forms of radiation used as well as by the intellectual context in which the scientists involved were educated and in which they worked.

PRODUCING PRECISION THROUGH QUALITY

Kaufmann's Search for Improved Precision

In 1881, J. J. Thomson suggested that a moving charged sphere would move not only through its own electrostatic field but also through the magnetic field induced by its motion, and that this entailed "an increase in mass of the moving sphere" in the form of a change in its inertia.[8] By the end of the 1800s, many theoreticians therefore divided the electron's total mass into

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[6] Kelley Wilder, "Visualizing Radiation: The Photographs of Henri Becquerel," in *Histories of Scientific Observation*, ed. Lorraine Daston and Elizabeth Lunbeck (Chicago: University of Chicago Press, 2011), 349–68, on 362.

[7] See also Kelley Wilder, *Photography and Science* (London: Reaktion Books 2009), and Gregg Mitman and Kelley Wilder, *Documenting the World: Film, Photography, and the Scientific Record* (Chicago: University of Chicago Press, 2016).

[8] J.J. Thomson, "On the Electric and Magnetic Effects Produced by the Motion of Electrified Bodies," *PM* 11 (1881): 229–49, on 230.

a constant, mechanical part—often called its real mass—and a velocity-dependent, electromagnetic part (also called its apparent mass).[9] Experimental evidence, however, was still mostly lacking.

At the time, there was already a well-established practice of determining the charge-to-mass ratio, and hence the mass, of low-velocity cathode rays: these would be deflected by means of electric or magnetic fields, and from the measured deflections one could then infer a charge-to-mass ratio value. Kaufmann himself,[10] together with S. Simon,[11] had already made a name in this field for having obtained a charge-to-mass ratio value[12] that many considered to be the most precise available.[13] Thomson had also shown, however, that velocity-dependent increases in mass would become more pronounced with increasing velocity,[14] and further elaborations of this suggested that it would become discernible only with velocities close to that of light. Since cathode rays can attain only much lower velocities, it was generally believed

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[9] Oliver Heaviside, "On the Electromagnetic Effects Due to the Motion of Electrification through a Dielectric," *PM* 27 (1889): 324–39; G.F.C. Searle, "On the Steady Motion of an Electrified Ellipsoid," *PM* 44 (1897): 329–41; Theodor des Coudres, "Handliche Vorrichtung zur Erzeugung Lenard'scher Strahlen und einige Versuche mit solche Strahlen," *AdP* 298 (1889): 134–44; Hendrik Antoon Lorentz, "Simplified Theory of Electrical and Optical Phenomena in Moving Systems," *Koninklijke Akademie van Wetenschappen te Amsterdam, Section of Sciences, Proceedings* 1 (1899): 427–44; Wilhelm Wien, "Ueber die Möglichkeit einer elektromagnetischen Begründung der Mechanik," *AdP* 310 (1901): 501–13.

[10] Walter Kaufmann, "Nachtrag zu der Abhandlung: 'Die magnetische Ablenkbarkeit der Kathodenstrahlen, etc.'" *AdP* 298 (1897): 596–98; "Die magnetische Ablenkbarkeit electrostatisch beeinflusster Kathodenstrahlen," *AdP* 301 (1898): 431–39.

[11] S. Simon, "Ueber das Verhältnis der elektrischen Ladung zur Masse der Kathodenstrahlen," *AdP* 305 (1899): 589–611.

[12] This value was $e/m_0 = 1.8647 \cdot 10^7$ electromagnetic units/gram, with the subscript 0 denoting low velocities. Miller (n. 2, p. 45) describes this system of units as follows (with the symbols changed for consistency): "In the Gaussian [centimeter-gram-second] system of units the unit for the elementary electric charge [ε] is an electrostatic unit (esu) or statcoulomb. Circa 1905, experimentalists used the absolute electromagnetic system of units in which the unit for the elementary charge [e] is an electromagnetic unit (emu) or abcoulomb. The relation between [ε and [e] is [$e = \varepsilon/c$]."

[13] W. Seitz, "Vergleich einiger Methoden zur Bestimmung der Grösse ε/μ bei Kathodenstrahlen," *AdP* 313 (1902): 233–43, on 234; Pierre Currie, "Neuere Untersuchungen über Radioaktivität," *PZ* 5 (1904): 281–88, on 284; August Becker, "Messungen an Kathodenstrahlen," *AdP* 322 (1905): 381–471, on 383; Paul Langevin, "The Relations of Physics of Electrons to Other Branches of Science," in *Congress of Arts and Sciences, Universal Exposition, St. Louis 1904* 4 (1906): 121–56, on 145.

[14] J.J. Thomson, *Notes on Recent Researches in Electricity and Magnetism* (Oxford: Clarendon Press, 1893): 21.

they could not provide insight into the velocity-dependency (later experiments indicated, however, that this was possible after all).[15]

Around the same time, Henri Becquerel, Ernst Dorn, Friedrich Giesel, and others started experimenting with β-rays, which were believed to be much faster than cathode rays (and possibly fast enough to make the effect discernible). Measuring their properties proved difficult, however. Cathode rays were relatively easy to study because of their bright, fluorescent glow. β-rays, on the other hand, could only be observed, as Dorn put it, "with well-rested eyes in a fully darkened room[, and] under these circumstances it is extremely difficult to obtain quantitative information."[16] Scientists therefore attempted to capture their deflections photographically, so they could be measured afterward. These measurements suggested *e/m*-values of the same order of magnitude as cathode rays, and *v*-values close to that of light. However, they also revealed that this method had its issues. As Ernest Rutherford put it:

> The photographic method is very slow and tedious, and admits only of the roughest measurements. Two or three days' exposure to the radiation is generally required to produce any marked effect on the photographic plate. In addition, when we are dealing with very slight photographic action, the fogging of the plate, during the long exposures required, by the vapours of the substances, is liable to obscure the result.[17]

Because of these issues, it was difficult to precisely identify the actual radiation traces: as Becquerel put it, this "remained principally an issue of appreciation" (see figure 1 for one of Becquerel's photographic plates).[18]

In 1901, Kaufmann claimed that the blurriness arose because β-rays consist of electrons with different velocities. When they are then deflected by

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[15] H. Starke, "Die magnetische und elektrische Ablenkbarkeit reflektierter und von dünnen Metallblättchen hindurchgelassener Kathodenstrahlen" *VDPS* 5 (1903): 14–22; Adolf Bestelmeyer, "Spezifische Ladung und Geschwindigkeit der durch Röntgenstrahlen erzeugten Kathodenstrahlen," *AdP* 335 (1906): 429–47; Erich Hupka, "Beitrag zur Kenntnis der trägen Masse bewegter Elektronen," *AdP* 336 (1909): 169–204; C.A. Proctor, "The Variation with Velocity of *e/m* for Cathode Rays," *Physical Review* 30 (1910): 53–61.

[16] Ernst Dorn, "Elektrostatische Ablenkung der Radiumstrahlen," *Abhandlungen der naturforschenden Gesellschaft zu Halle* 22 (1901): 47–50, on 49.

[17] Ernest Rutherford, "Uranium Radiation and the Electrical Conduction Produced by It," *PM* 47 (1899): 109–63, on 110.

[18] Henri Becquerel, "Déviation du rayonnement du radium dans un champ électrique," *Comptes Rendus des Séances de l'Académie des Sciences* 130 (1900): 809–15, on 813.

FIGURE 1. A published photolithograph from a photographic plate produced by Becquerel. *Source*: Henri Becquerel, 1903, *Recherches sur une propriété nouvelle de la matière: Activité radiante spontanée ou radioactivité de la matière*. Paris: Institut de France.

either an electric or magnetic field separately, as was common practice following cathode ray research, "it is impossible to determine with the required precision the parts [of the velocity spectrum] that belong to separate deflections."[19] This could be overcome, he claimed, by combining both deflections perpendicularly. This meant that if the ray's direction of travel was taken to be the *x*-direction (here into the paper), they would be deflected in the *y*-direction by an electric field (with *y*-direction) and at the same time in the horizontal *z*-direction by a magnetic field (also with *y*-direction). In this way, Kaufmann claimed, one obtained a plate displaying a photographic

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[19] Walter Kaufmann, "Methode zur exakten Bestimmung von Ladung und Geschwindigkeit der Becquerelstrahlen," *PZ* 2 (1901): 602–3, on 602.

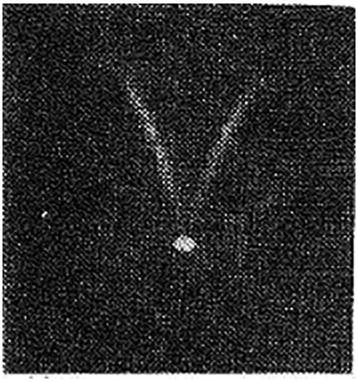

FIGURE 2. A published photolitograph from a photographic plate produced by Kaufmann. *Source*: Kaufmann, "Ueber die 'Elektromagnetische Masse'" (n. 25).

curve with disentangled velocities (see figure 2 for an example, which contains two curves; more on this below).

These curves, Kaufmann claimed,[20] directly displayed the dependency of the electron's mass on its velocity. Depending on their velocity, their inertia with respect to the applied fields would be different, in such a way that the fastest electrons would be deflected least and would end up closest to the zero-point formed by undeflected rays (the big bright spot at the bottom, formed before the experiment), while the slower electrons would be deflected more, and would end up further removed from the zero-point. By measuring a dot's deflection from the zero-point and comparing it with the deflection of other traces, one could then obtain information about how the electron's inertial mass changed with velocity.

The set-up functioned as follows: a piece of radium acted as the radiation source, emitting β-rays; after ensuring a vacuum, these rays would first travel through two capacitor plates subjecting them to an electric field; after passing through a diaphragm, they were subjected to a magnetic field induced by an external electromagnet; they would then end up on the photographic plate, leaving behind a trace. By combing a trace's distance from the zero-point with specific apparatus dimensions, Kaufmann could then infer the curvature of the deflected ray that had produced that

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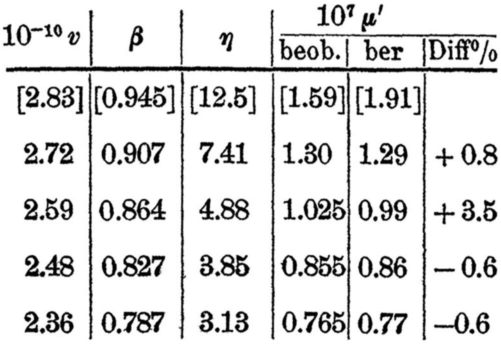
[20] Kaufmann, "Magnetische und electrische Ablenkbarkeit" (n. 3), 144.



$10^{-10} v$	β	η	$10^7 \mu'$		
			beob.	ber	Diff%
[2.83]	[0.945]	[12.5]	[1.59]	[1.91]	
2.72	0.907	7.41	1.30	1.29	+ 0.8
2.59	0.864	4.88	1.025	0.99	+ 3.5
2.48	0.827	3.85	0.855	0.86	− 0.6
2.36	0.787	3.13	0.765	0.77	−0.6

FIGURE 3. Kaufmann's 1901 measurement results. *Source*: Kaufmann, "magnetische und electrische Ablenkbarkeit" (n. 3), 154.

particular trace. Given the applied field strengths, one could then derive the velocity β (equal to *v*/*c*, with *c* the velocity of light) and the corresponding charge-to-mass ratio *e*/*m*.[21]

The obtained values (see figure 3) indicated that the fastest electrons approximated the velocity of light (β = 0.945*c*), and that with increasing velocity there was a strong decrease in *e*/*m* (increase in μ in figure 3). This suggested "a not inconsiderable amount of 'apparent' mass."[22] To determine this amount precisely, Kaufmann then used an electron-model proposed by George Frederick Charles Searle,[23] which provided an interpolation graph for the entire velocity spectrum (see figure 4). This indicated that at least one-third of the electron's mass was electromagnetic, and that this contribution increased with velocity.[24]

To obtain a photographic plate that contained a sufficient number of traces, Kaufmann's set-up had to run three to four days. It was of the utmost importance that it remained absolutely stable throughout this period as otherwise the measurements could become prone to subjective influences. As Kaufmann put it in a later paper:

> Targeting the crosshair on the middle of a curve with not completely sharp borders is an act of subjective judgment, for which even very small

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[21] Miller, *Special Theory of Relativity* (n. 2), 47–54.

[22] Kaufmann, "Magnetische und electrische ablenkbarkeit" (n. 3), 153.

[23] Searle, "Steady Motion" (n. 9).

[24] Kaufmann, "Magnetische und electrische Ablenkbarkeit" (n. 3), 155.

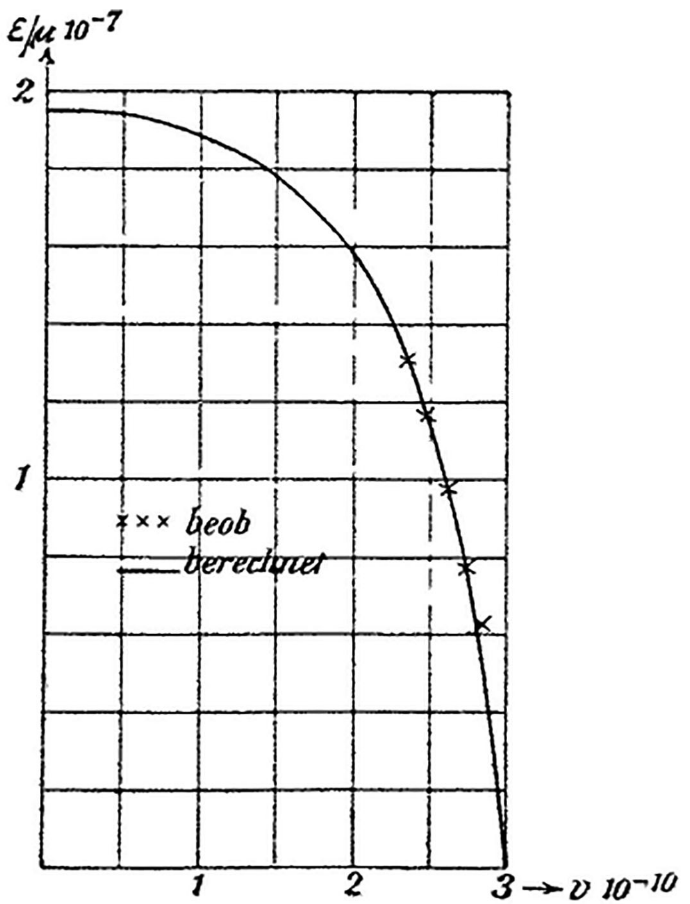

FIGURE 4. Kaufmann's interpolated graph. *Source*: Kaufmann, "magnetische und electrische Ablenkbarkeit" (n. 3), 154.

> irregularities of the plate are of major importance. A small bright or dark spot on the plate, resulting out of fabrication- or development errors, influences the judgment in a decisive way.[25]

In 1901, Kaufmann tried to rule out the influence of such subjective judgments on the measurement process in different ways. To measure a trace's distance from the zero-point, he made use, for example, of an Abbe comparator modified specifically for the measurement of curved lines (by adding

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[25] Walter Kaufmann, "Ueber die 'Elektromagnetische Masse' der Elektronen," *NGWG* 1903, 90–103, on 93.

two movable microscopes with scales).[26] He also measured each trace repeatedly (ten times), and had graduate students redo them, to diminish as much as possible the influence of individual errors.[27] In this way, he became convinced that there was too much room for error in the measurement of the highest velocities: their deflections were minimal and hence difficult to distinguish from the zero-point and from the mirrored curve. Kaufmann therefore excluded them from his calculations (hence they are bracketed in figure 3).[28]

Kaufmann also built in several ways to evaluate the adequacy of his experiments. He first of all compared the shape of the obtained interpolation graph with that of the photographic curves. Second, halfway through an experimental run, he would invert the directions of the applied field so that the photographic plate would contain two curves that, if the set-up remained stable, would be mirrored symmetrically around the y-axis.[29] And third, he also inferred a low-velocity charge-to-mass ratio value from his results, and compared that with the value considered the most precise one available at the time, that is, Simon's ($1.8647 \cdot 10^7$, see footnote 12). On all three criteria, his experiments had performed adequately, according to Kaufmann:[30] the interpolation graph and the photographic curve were strikingly similar, the two photographic curves were highly symmetric, and the e/m_0-value obtained ($1.95 \cdot 10^7$) was satisfactorily close to Simon's. Hence, Kaufmann concluded, his plates could be taken as sharp and clear.

In 1903, Kaufmann carried out a second experimental run, with improved materials: he used a stronger battery, a more potent radiation source, and a better vacuum pump. The goal of these changes was, primarily, to improve the quality of the plates. That this had been achieved was shown, according to Kaufmann, by the fact that the e/m_0-value ($1.845 \cdot 10^7$) obtained was significantly closer to Simon's ($1.8647 \cdot 10^7$) than that from his previous experiments ($1.95 \cdot 10^7$).[31] A second objective of these improvements was to reduce the production time, which was also achieved, as producing a plate now took forty

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[26] Kaufmann, "Über die Konstitution" (n. 1), 517–19.

[27] Kaufmann, "Magnetische und electrische Ablenkbarkeit" (n. 3), 150.

[28] Kaufmann, "Magnetische und electrische Ablenkbarkeit" (n. 3), 154.

[29] Kaufmann, "Magnetische und electrische Ablenkbarkeit" (n. 3), 145–48.

[30] Kaufmann, "Magnetische und electrische Ablenkbarkeit" (n. 3), 152.

[31] Kaufmann, "Ueber die 'Elektromagnetische Masse'" (n. 25), 102.

hours rather than up to four days. Because of this reduction in time, Kaufmann was also able to obtain more plates: he now produced four plates, each providing between seven and fifteen useable traces.[32]

This increase in number of plates also posed a new challenge, however, since how could one combine data from plates that varied in sharpness and clarity? To overcome this, Kaufmann weighed the data obtained in terms of plate quality, which he quantified in terms of two constants: an apparatus constant obtained directly from the apparatus dimensions during the plate's production, and a curve constant obtained from the photographic curve. The smaller the difference between the two, the higher the weight of data from this plate in his calculations.[33]

These constants also offered a way to obtain a velocity-dependency expression that did not depend as directly on one particular electron-model. Hence, Kaufmann could now use his experiments to evaluate such models. This led him to claim that his results completely confirmed Max Abraham's electron-model. According to this model, the electron was a rigid charged sphere with a completely electromagnetic mass (and zero mechanical mass),[34] and Kaufmann, a colleague of Abraham in Göttingen at the time, almost literally repeated Abraham's conclusion that the electron's "mass is completely electromagnetic in nature."[35]

A year later, in 1904, Hendrik Antoon Lorentz showed that his electron-model, which was deformable with velocity rather than rigid as Abraham's, entailed velocity-dependency expressions that, while different from Abraham's, fitted Kaufmann's 1903 results equally well.[36] Alfred Bucherer also put forward an electron-model.[37] It was completely electromagnetic in nature, like Abraham's, and it deformed with velocity, like Lorentz's, but

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[32] Kaufmann, "Ueber die 'Elektromagnetische Masse'" (n. 25), 90–91.

[33] Kaufmann, "Ueber die 'Elektromagnetische Masse'" (n. 25), 96–97; Miller, *Special Theory of Relativity* (n. 2), 61–67.

[34] Max Abraham, "Dynamik des Elektrons," *NGWG* (1902): 20–41; "Prinzipien der Dynamik des Elektrons," *AdP* 315 (1902): 105–79.

[35] Abraham, "Dynamik des Elektrons" (n. 34), 40; Kaufmann, "Ueber die 'Elektromagnetische Masse'" (n. 25), 103.

[36] Hendrik Antoon Lorentz, "Electromagnetic Phenomena in a System Moving with Any Velocity Smaller Than That of Light," *Koninklijke Akademie van Wetenschappen te Amsterdam, Section of Sciences, Proceedings* (1904), 809–31.

[37] Alfred Bucherer, *Mathematische Einführung in die Elektronentheorie* (Leipzig: B.G. Teubner, 1904).

it deformed in a different way such that it provided still different velocity-dependency expressions. And Albert Einstein, in 1905,[38] showed that Lorentz's expressions could also be obtained from the principle of relativity and the postulate of the constancy of the velocity of light for any moving body in general.[39] Kaufmann therefore carried out new experiments to decide between these (results published in 1906).[40]

To increase the stability of the fields and vacuum, Kaufmann used a stronger radiation source, more powerful batteries and magnets, and a new, self-designed vacuum-pump (about which he published a separate article[41]). To obtain as precise apparatus and curve constants as possible, he also designed his set-up such that "the utmost attention was paid to achieve absolute immutability and exact measurability of all dimensions in question."[42] Kaufmann obtained five photographic plates, each of which took between forty and forty-eight hours to produce, and which provided him with forty-nine data points in total. The results were clear:[43] the Lorentz-Einstein theory deviated significantly more from the data, and hence "the attempt to base the whole of physics, including electrodynamics and optics, on the principle of relative motion has to be considered a failure."[44]

Bucherer's Compensated Trajectories

Kaufmann's results surprised and impressed many, as is shown by the fact that they were widely passed around and commented on (e.g., by Arnold Sommerfeld,[45]

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[38] Albert Einstein, "Zur Elektrodynamik bewegter Körper," *AdP* 322 (1905): 891–921.

[39] For an extensive comparison of these models, see Michel Janssen and Matthew Mecklenburg, "From Classical to Relativistic Mechanics: Electromagnetic Models of the Electron," in *Interactions: Mathematics, Physics, and Philosophy, 1860–1930*, ed. V.F. Hendricks, K.F. Jørgensen, J. Lützen and S.A. Pedersen (Dordrecht: Springer, 2006).

[40] Kaufmann, "Über die Konstitution" (n. 1).

[41] Walter Kaufmann, "Eine rotierende Quecksilberluftpumpe," *Zeitschrift für Instrumentenkunde* 25 (1905), 129–33.

[42] Kaufmann, "Über die Konstitution" (n. 1), 496.

[43] See Miller, *Special Theory of Relativity* (n. 2), for an extensive discussion (pp. 226–32).

[44] Kaufmann, "Über die Konstitution" (n. 1), 534.

[45] Letter from Sommerfeld to Wien dated December 14, 1905, in *Arnold Sommerfeld, Wissenschaftlicher Briefwechsel, Band 1: 1892–1918*, ed. Michael Eckert and Karl Märker (Berlin: Verlag für Geschichte der Wissenschaft und der Technik, 2000), 251.

Abraham,[46] Kaufmann,[47] Max Planck,[48] Bucherer,[49] Wilhelm Wien,[50] Rutherford,[51] Lorentz,[52] Henri Poincaré,[53] and Paul Langevin[54]). Not all were convinced, however. Einstein suspected systematic errors, although he also accepted that if that was not the case, the relativity principle's validity would have to be restricted.[55] And Planck suggested that Kaufmann's *e/m*-values could be problematic[56] because certain data-points entailed velocities surpassing that of light, which suggested that remaining air in the set-up had ionized.[57] Both therefore argued that definite conclusions required more experiments.

In 1908, Bucherer, Kaufmann's colleague in Bonn at the time, claimed he had carried out significantly improved experiments. Whereas Kaufmann had employed parallelly oriented fields for perpendicular deflections, Bucherer used a perpendicular field orientation to obtain parallel deflections. This forced Bucherer to also change the direction of travel. If he would have made the rays

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[46] Max Abraham, *Theorie der Elektrizität, Zweiter Band: Elektromagnetische Theorie der Strahlung*, (Leipzipg: B.G. Teubner, 1905), 199.

[47] Remark made by Kaufmann after a talk by Max Planck, "Die Kaufmannschen Messungen der Ablenkbarkeit der β–Strahlen in ihrer Bedeutung für die Dynamik der Elektronen," *PZ* 7 (1906): 753–61, on 759.

[48] Letter from Planck to Kaufmann dated October 4, 1907, stored at the Handschriftenabteilung of the Staatsbibliothek zu Berlin (signature Autogr. I/1299 -1).

[49] Letter from Bucherer to Einstein dated September 9, 1908, in *The Collected Papers of Albert Einstein, Volume 5: The Swiss Years: Correspondence, 1902–1914,* ed. Martin J. Klein, A.J. Kox and Robert Schulmann (Princeton, NJ: Princeton University Press, 1994), 136.

[50] Remark made by Wien after a talk by Alfred Bucherer, "Messungen an Becquerelstrahlen. Die experimentelle Bestätigung der Lorentz-Einsteinschen Theorie," *PZ* 9 (1908): 755–62, on 761.

[51] Letter from Rutherford to Kaufmann dated May 27, 1913, stored at the Handschriftenabteilung of the Staatsbibliothek zu Berlin (signature Autogr. I/1294).

[52] Letter from Lorentz to Poincaré dated March 8, 1906, in *The Scientific Correspondence of H.A. Lorentz Volume I*, ed. A.J. Kox (Dordrecht: Springer, 2008), 203.

[53] Henri Poincaré, "Sur la dynamique de l'électron," *Rendiconti del Circolo Matematico di Palermo* 21 (1906), 129–75, on 132.

[54] Letter from Langevin to Kaufmann, dated November 27, 1905, stored at the Handschriftenabteilung of the Staatsbibliothek zu Berlin (signature Autogr. I/1298).

[55] Albert Einstein, "Über das Relativitätsprinzip und die aus demselben gezogenen Folgerungen," *Jahrbuch der Radioaktivität und Elektronik* 4 (1907): 411–62, on 439.

[56] Planck, "Kaufmannsche Messungen" (n. 47), 757–58.

[57] Max Planck, "Nachtrag zu der Besprechungen der Kaufmannschen Ablenkungsmessungen," *VDPS* 9 (1907): 301–5. This gave rise to a small discussion on the ionization of gases see Walter Kaufmann, "Bemerkungen zu Herrn Plancks: 'Nachtrag zu der Besprechung der Kaufmannschen Messungen,'" *VDPS* 9 (1907): 667–73; Johannes Stark, "Bemerkungen zu Herrn Kaufmanns Antwort auf einen Einwand von Herrn Planck," *VDPS* 10 (1908): 14–16; Walter Kaufmann, "Erwiderung an Herrn Stark," *VDPS* 10 (1908): 91–95.

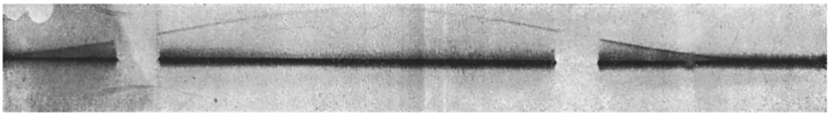

FIGURE 5. A published photolithograph from a photographic plate produced by Bucherer. *Source*: Bucherer, "Die experimentelle Bestätigung" (n. 64).

travel in a straight line from source to plate, as Kaufmann had done, the parallel deflections would make the traces overlap again. He therefore placed the radiation source in the middle of a circular set-up so that the rays would travel in all directions.

The source was placed between two capacitor plates, and the whole was surrounded by an electromagnet. With no fields applied, the radiation then traced a horizontal line on the photographic material covering the inner wall (the bottom of the black strip on figure 5). With applied fields, the electrons would follow what Bucherer called a "compensated trajectory": depending on their velocity and the applied field strengths, they would describe a specific angle α with respect to the magnetic field direction (within the horizontal capacitor plane). Once past the capacitor plates, the electrons were subject solely to the magnetic field, which then added to their compensated trajectory a vertical deflection (perpendicular to the capacitor plane), making them end up either above or below the undeflected line. Given the applied field strengths and the set-up dimensions, one could then infer velocity and corresponding charge-to-mass ratio from a trace's angle α and its vertical deflection (with respect to the undeflected line).[58]

Bucherer published results obtained from around five plates (see figure 6; he did not specify why he grouped experiments 10 and 11 together). He chose to measure only one value per plate, the maximal vertical deflection peak, from which he then derived the corresponding low-velocity charge-to-mass ratio e/m_0-value according to the different theories. The theory providing the most stable e/m_0-value for different plates was then to be preferred. In this way, Bucherer claimed, one could obtain a precise velocity-dependency curve and a decision between the different theories without having to carry out the complex measurements and calculations required for apparatus and curve constants.[59] The theory that provided the

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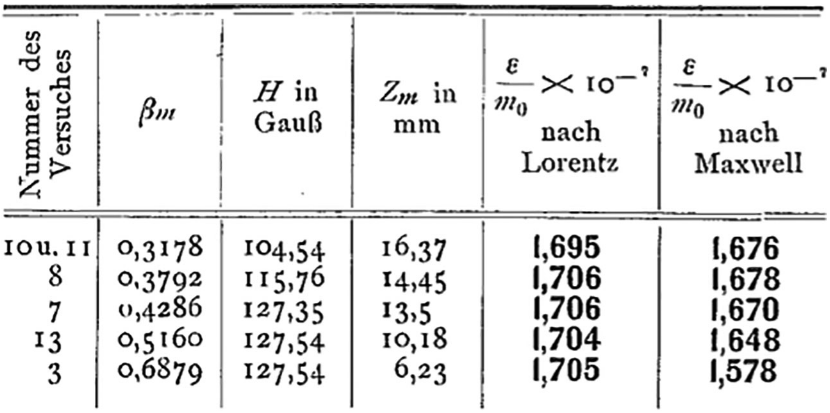
[58] Bucherer, "Messungen an Becquerelstrahlen" (n. 50), 757–58.

[59] Bucherer, "Messungen an Becquerelstrahlen" (n. 50), 759.



Nummer des Versuches	β_m	H in Gauß	Z_m in mm	$\frac{\varepsilon}{m_0} \times 10^{-7}$ nach Lorentz	$\frac{\varepsilon}{m_0} \times 10^{-7}$ nach Maxwell
10 u. 11	0,3178	104,54	16,37	1,695	1,676
8	0,3792	115,76	14,45	1,706	1,678
7	0,4286	127,35	13,5	1,706	1,670
13	0,5160	127,54	10,18	1,704	1,648
3	0,6879	127,54	6,23	1,705	1,578

FIGURE 6. Bucherer's results (the Maxwell-values refer to Abraham's theory).
Source: Bucherer, "Messungen an Becquerelstrahlen" (n. 50), 760.

most stable e/m_0-value was the Lorentz-Einstein theory (e/m_0 around $1.705 \cdot 10^7$).[60] This result, Bucherer claimed, not only offered a definitive confirmation of this theory. It equally well provided a new standard of evaluation for future measurements (in replacement of Simon's value), since the divergence between his value and earlier ones indicated that "measurements carried out until now [. . .] have been carried out under barely controlled circumstances."[61]

The validity of his results, Bucherer pointed out, was conditional on there being only few 'spurious rays,' that is, rays that, because they deviated from the expected deflection angle α, would displace and blur the photographic curve. According to Bucherer, however, they posed no issue: "I have calculated the deflection of these extreme rays and have convinced myself that they do not significantly influence the results."[62] In the question session following Bucherer's presentation, however, Adolf Bestelmeyer immediately asked for detailed dimensional measurements, since as long as these were lacking, the actual influence of such spurious rays could not be evaluated. Bucherer replied by showing one of his photographic plates, and by claiming that if any such spurious rays had been at work, the curve width would have been different.[63]

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[60] Bucherer, "Messungen an Becquerelstrahlen" (n. 50), 760.

[61] Bucherer, "Messungen an Becquerelstrahlen" (n. 50), 759.

[62] Bucherer, "Messungen an Becquerelstrahlen" (n. 50), 760.

[63] Bucherer, "Messungen an Becquerelstrahlen" (n. 50), 760–61.

Bestelmeyer was not convinced. Since the production of a plate took up to sixty hours,[64] it was important to know how field stability was maintained to prevent spurious rays. Without detailed dimensional measurements, there was no way to evaluate Bucherer's e/m_0-calculations.[65] Moreover, merely pointing at the photographic curves did not do: without precise measurements of, for example, the space between the capacitor plates and their distance from the photographic plate, "it is not possible to state exactly what one focuses on when one measures a photographic plate."[66]

Bucherer did not agree: "[T]hat I have succeeded in keeping the magnetic field very stable—with the help of others, of course—can be seen from the sharpness of the obtained curves." [67] Moreover, Bucherer continued,[68] in experiments that specifically investigated the influence of spurious rays (by varying the capacitor plate width and their distance from the photographic plate), Kurt Wolz had obtained e/m_0-values in line with Bucherer's.[69] And while Bestelmeyer decided not to continue the discussion, because he found Bucherer's tone increasingly polemical,[70] Bucherer claimed in a final paper that detailed dimensional measurements were not necessary: his procedure improved upon Kaufmann's by significantly simplifying it, and hence did not depend as much upon such dimensional determinations.[71] Moreover, he had recently learned that J. Classen had obtained very similar e/m_0-values,[72] which confirmed, Bucherer concluded, both the validity of his own experimental results and his claim that his e/m_0-value offered a new measurement standard.[73]

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[64] Alfred Bucherer, "Die experimentelle Bestätigung des Relativitätsprinzip," *AdP* 333 (1909): 513–36, on 520.

[65] Adolf Bestelmeyer, "Bemerkungen zu der Abhandlung Hrn. A. Bucherers: 'Die experimentelle Bestätigung des Relativitätsprinzip,'" *AdP* 335 (1909): 166–74, on 168.

[66] Bestelmeyer, "Bemerkungen zu der Abhandlung (n. 65), 171.

[67] Alfred Bucherer, "Antwort auf die Kritik des Hrn. E. Bestelmeyer bezüglich meiner experimentellen Bestätigung des Relativitätsprinzips," *AdP* 335 (1909): 974–86, on 975.

[68] Bucherer, "Antwort auf die Kritik (n. 67), 977.

[69] Kurt Wolz, "Die Bestimmung von e/m_0," *AdP* 335 (1909): 273–88.

[70] Adolf Bestelmeyer, "Erwiderung auf die Antwort des Hrn. A.H. Bucherer," *AdP* 337 (1910): 231–35.

[71] Alfred Bucherer, "Erwiderung auf die Bemerkungen des Hrn. A. Bestelmeyer," *AdP* 338 (1910): 853–56, on 856.

[72] J. Classen, "Eine Neubestimmung von e/m für Kathodenstrahlen," *PZ* 9 (1908): 762–65.

[73] Bucherer, "Erwiderung auf die Bemerkungen" 1910 (n. 71), 856.

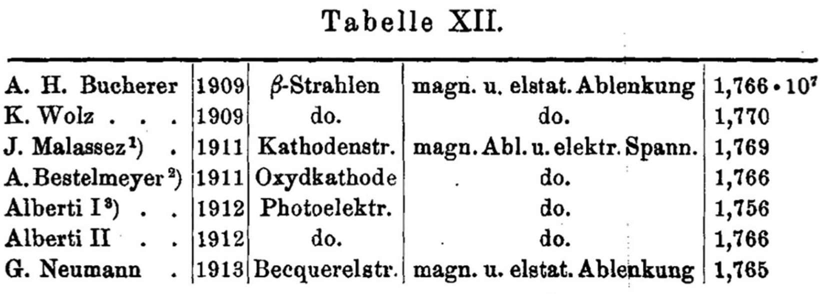

Tabelle XII.

A. H. Bucherer	1909	β-Strahlen	magn. u. elstat. Ablenkung	1,766 • 10^7
K. Wolz . . .	1909	do.	do.	1,770
J. Malassez[1]) .	1911	Kathodenstr.	magn. Abl. u. elektr. Spann.	1,769
A. Bestelmeyer[2])	1911	Oxydkathode	do.	1,766
Alberti I[3]) . .	1912	Photoelektr.	do.	1,756
Alberti II . .	1912	do.	do.	1,766
G. Neumann .	1913	Becquerelstr.	magn. u. elstat. Ablenkung	1,765

FIGURE 7. Neumann's comparison with earlier e/m_0-values. *Source*: Neumann, "Die träge Masse" (n. 74), on 576.

Neumann's Replication of Bucherer's Experiments

This discussion was picked up again in 1914 by Günther Neumann, who re-used and improved Bucherer's original set-up.[74] In response to Bestelmeyer's demand for dimensional measurements, he used many different precision instruments (often specifically designed or adapted): an Abbe-Fizeau interferometer for the dimensions of the capacitor plates,[75] a Hartmann & Braun milli-ampèremeter and a Rapps compensator from Siemens & Halske for the strength of the current responsible for the magnetic field,[76] and a dividing engine, specifically designed following a proposal by Heinrich Kayser, to help with the measurement of the photographic curves.[77] By means of stronger batteries, radiation source, and vacuum pump, he was also able to reduce the production time significantly (to between 7 and 16 hours).[78] The obtained e/m_0-values for the maximal deflection peak were in line with Bucherer's,[79] and the mean value was close to the values obtained from Bucherer onward (see figure 7).

Neumann was also able to significantly improve upon the number of plates produced: whereas Kaufmann and Bucherer had produced up to five plates, he had obtained fifty-five plates.[80] He could really use only twenty-six of them, however, since he noticed that whenever the distance between capacitor and photographic plate became too wide, or when the velocity went above

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[74] Günther Neumann, "Die träge Masse schnell bewegter Elektronen," *AdP* 350 (1914): 529–70.

[75] Neumann, "Die träge Masse (n. 74), 535.

[76] Neumann, "Die träge Masse (n. 74), 546

[77] Neumann, "Die träge Masse (n. 74), 555.

[78] Neumann, "Die träge Masse (n. 74), 554.

[79] Neumann, "Die träge Masse (n. 74), 574.

[80] Neumann, "Die träge Masse (n. 74), 557.

$\beta = 0.75c$, the photographic curves became wide and blurry.[81] The reasons for this, according to Neumann, could be many. It could be brought about by spurious rays (as Bestelmeyer had suggested for Bucherer's experiments) or by ionization of the remaining air (as Planck had suggested for Kaufmann's experiments).[82] It could also be caused by instabilities in the applied field, which could result out of the presence of a nearby tramway (which forced him to work at night),[83] or out of fluctuations in the city's electricity network:

> [T]he urban voltage fluctuated constantly, so that the current had to be continuously readjusted. During the first test run, I did the readjustments on my own. Since in the long run, however, the observer's attention wanes despite the most intense concentration—the exposure time for a double [i.e., mirrored] recording varies between 7 and 16 hours –, I later had myself relieved every two hours by a number of ladies and gentlemen working in the Physical Institute.[84]

PRODUCING PRECISION THROUGH QUANTITY

All experiments discussed to this point investigated the velocity-dependency of mass by means of β-rays. The reason for this was that it was often believed that only these rays could attain velocities high enough to make any change in mass discernible.[85] Over time, however, it became clear that cathode rays could equally well be used to bring about the effect experimentally, although their velocity was significantly lower (see footnote 15). Most of these experiments did not make use of photographic plates because the fluorescent nature of cathode rays made real-time measurements quite easy. However, one series of experiments, by Charles-Eugène Guye and his doctoral student Charles Lavanchy in 1913 (published in 1916),[86] did make use of photographic plates to capture the effect as produced by cathode rays. Their method, which was the first to study the velocity-dependency by capturing cathode rays on photographic plates

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[81] Neumann, "Die träge Masse (n. 74), 555–58.

[82] Neumann, "Die träge Masse (n. 74), 574.

[83] Neumann, "Die träge Masse (n. 74), 541.

[84] Neumann, "Die träge Masse (n. 74), 554.

[85] For such claims, see e.g., Walter Kaufmann, "Die Entwicklung des Elektronenbegriffs," *PZ* 3 (1901): 9–15, on 14; Abraham, "Prinzipien der Dynamik" (n. 34), 106.

[86] Charles-Eugène Guye and Charles Lavanchy, "Vérification expérimentale de la formule de Lorentz-Einstein par les Rayons cathodiques de grande vitesse," *Archives des Sciences Physiques et Naturelles de Genève* (1916): 286–299, 353–373, 441–448.

according to Yacin Karim (from whose PhD dissertation on Guye's work[87] this section draws extensively),[88] will be the subject of this section.

To understand Guye and Lavanchy's photographic method, we first need to discuss some of Guye's earlier experiments, which he carried out in 1907 with another doctoral student, Simon Ratnowsky (published in 1910).[89] Following Bestelmeyer (see footnote 15), they subjected cathode rays to perpendicularly oriented electric and magnetic fields, which deflected them vertically with respect to an undeflected spot (depending on the polarity of the capacitor plates, they would end up either above or below the undeflected spot). Drawing on work by Paul Villard and Jean Malassez,[90] Guye and Ratnowsky adapted this earlier approach in such a way that they could split the rays depending on their velocity. Each deflection would leave behind, more specifically, two different traces below or above the undeflected dot: one brought about by higher velocity rays (which was closer to the undeflected spot), and one more removed from the undeflected point, formed by slower electrons.[91] During the experimental run, they would then measure the distance of both points from the undeflected spot, and would do the same after reversing the polarization. In this way, they obtained four data points per deflection, and in total, they were able to carry out twenty-seven such deflections. These measurements, they claimed, confirmed Lorentz's theory (Einstein was not mentioned).[92]

A few years later, Guye became convinced that neither his own nor other earlier experiments had achieved the required precision to make such claims (his paper with Lavanchy offers a detailed discussion of many earlier experiments).[93] Together with Lavanchy, he therefore carried out new experiments. While the general approach remained the same—split cathode rays into two

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[87] Yacin Karim, "Vers une vérification expérimentale de la théorie de la relativité restreinte: Réplication des expériences de Charles-Eugène Guye (1907–1921)" (Doctoral dissertation, Université Claude Bernard—Lyon I 2011). https://tel.archives-ouvertes.fr/tel-00839315

[88] Karim, "vérification expérimentale" (n. 87), 85.

[89] Charles-Eugène Guye and Simon Ratnowsky, "Sur la variation de l'inertie en fonction de la Vitesse dans les rayons cathodiques et sur la principe de relativité," *Comptes Rendus hebdomadaires des séances de l'Académie des sciences* 150 (1910): 326–329.

[90] Paul Villard, *Les Rayons Cathodiques* (Paris: Scientia, 1900); Jean Malassez "Sur la différence de potentiel sous laquelle sont produits les rayons cathodiques," *Comptes Rendus hebdomadaires des séances de l'Académie des sciences* 141 (1905): 884–86.

[91] Karim, "Vérification expérimentale" (n. 87), 163–83.

[92] Guye and Ratnowsky, "Variation" (n. 89), 329.

[93] Guye and Lavanchy, "Vérification" (n. 86), 288–92.

different velocities and deflect them vertically, while regularly reversing polarization—they would no longer measure in real time. Rather, they would now employ photographic plates:

> [T]he [previous] method did not allow for rapid determinations. [. . .] We therefore looked for a method that, while preserving the advantages of the previous one, improved it as much as possible by increasing both the rapidity of the determination and the precision of the dots. We have succeeded by opting for rapid photographic determination instead of the trial and error involved in multiple determinations of the same deflection.[94]

Guye and Lavanchy attempted to obtain such rapidity by making the photographic plate moveable with a screw. This allowed them to change the distance between source and plate in predetermined steps. They also placed a vertical slit between source and plate, which was moveable in the same way. In this way, they could create a vertical column consisting of both an undeflected and four deflected traces, and then fit another column of traces on the same photographic plate by turning the screw (for an example of the photographic plates produced by Guye and Lavanchy, see figure 8). Undeflected rays formed the horizontal middle row, while the upper and lower rows were produced by deflected rays: depending on the capacitor polarization and the rays' velocity, they would end up either above or below, and either closer or further removed from, the undeflected row.

In this way, Guye and Lavanchy created an experimental set-up that was, indeed, fairly rapid: it took them only about five seconds, they claimed, to produce one column of traces, and only a few minutes to produce a completely filled plate.[95] It also provided them with a significant amount of data points: they could fit between ten and eighteen columns on one photographic plate,[96] and they were able to produce around 150 such plates, which offered them in total more than 2,000 deflections (each consisting of four deflected traces).[97] This was such a large amount that they could not include them in their paper (according to Karim,[98] it took until 1921 before they were published).

Proceeding in this way provided quite a few advantages, according to Guye and Lavanchy. First, because the production time was so short, maintaining

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[94] Guye and Lavanchy, "Vérification" (n. 86), 297.

[95] Guye and Lavanchy, "Vérification" (n. 86), 360–63.

[96] Guye and Lavanchy, "Vérification" (n. 86), 360–63.

[97] Guye and Lavanchy, "Vérification" (n. 86), 442.

[98] Karim, "Vérification expérimentale" (n. 87), 155–56.

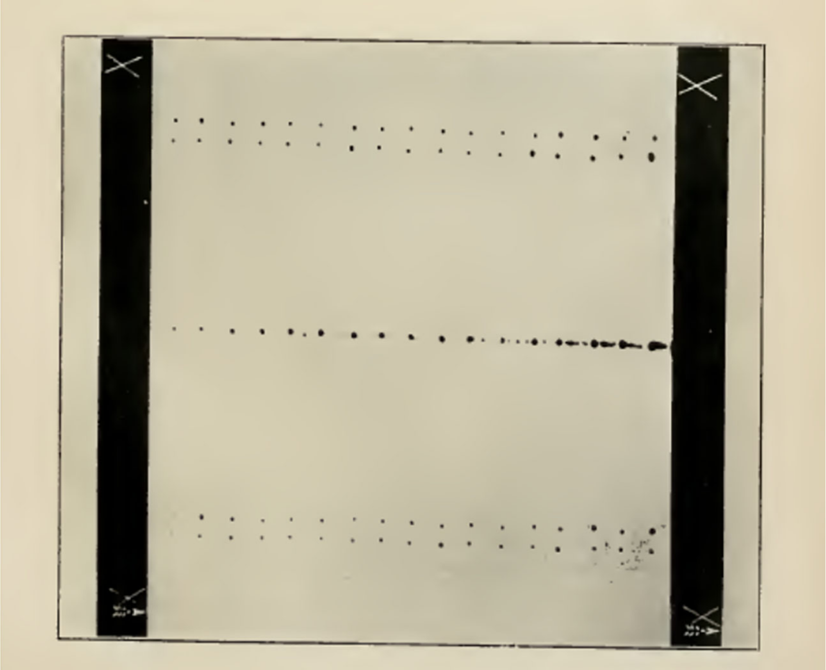

FIGURE 8. A published photolithograph from a photographic plate produced by Guye and Lavanchy. *Source*: Guye and Lavanchy, "Vérification" (n. 86), on 362–63.

the applied fields absolutely stable was no longer required: the time between two photographic determinations was too short to allow for any significant field fluctuations.[99] Moreover, the introduction of the vertical slit allowed them to significantly diminish the number of spurious rays disturbing the production of the plates, since most were stopped by the slit plate.[100] Because the radiation traces were arranged in straight horizontal and vertical lines, rather than in a curve as in earlier experiments, their measurement was also quite easy: according to Guye and Lavanchy, a simple ruler sufficed to determine their distance with precision.[101] And even if any errors were to disturb individual measurements, that was not a problem since "the large amount of measurements eliminates almost completely any random errors."[102]

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[99] Guye and Lavanchy, "Vérification" (n. 86), 365–68.
[100] Guye and Lavanchy, "Vérification" (n. 86), 361.
[101] Guye and Lavanchy, "Vérification" (n. 86), 363–65.
[102] Guye and Lavanchy, "Vérification" (n. 86), 373.

They then obtained a velocity-dependency expression by combining these measurement data with the approximately correct applied field strengths and with an e/m_0-value, for which they chose $1.77 \cdot 10^7$ because it was more or less in the middle between the higher e/m_0-values obtained by Kaufmann and Simon and the lower ones obtained by Bucherer and Neumann.[103] These calculations favored the Lorentz-Einstein formula over Abraham's,[104] but, as they pointed out already in the introduction, their results covered only a rather restricted part of the velocity spectrum (the cathode ray velocities at play were between $0.23c$ and $0.48c$).[105]

PRODUCING PRECISION VISUALLY

The Epistemic Value of Photographic Plates

All experiments discussed above aimed to determine the velocity-dependency of the electron's mass as precisely as possible: all experimentalists claimed that their experiments improved in some way on the earlier ones, and that because of these improvements the photographic plates produced allowed for more precision. Such precision was of the utmost importance, since, as Kaufmann pointed out, the difference between the different theories was very small.[106]

While all agreed that precision was the goal, there was less agreement on how it was to be achieved exactly. This can be seen from the fact that there are differences in how the scientists involved attempted to visualize the phenomenon under study as precisely as possible: while Kaufmann and Bucherer (and presumably also Neumann since he used the same set-up as Bucherer) produced a photographic curve, Guye and Lavanchy produced straight lines of dots.

These different ways of visualizing the velocity-dependency with precision indicate that the scientists involved had different stances with respect to what the photographic plates were intended to display exactly. For Kaufmann, Bucherer, and Neumann, each photographic plate in itself was supposed to offer a complete representation of how the electron's mass changed with velocity: each plate, as it were, was supposed to directly display as clearly and sharply as possible the velocity-dependency curve that the scientists involved

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[103] Guye and Lavanchy, "Vérification" (n. 86), 368–70.
[104] Guye and Lavanchy, "Vérification" (n. 86), 448.
[105] Guye and Lavanchy, "Vérification" (n. 86), 292.
[106] Kaufmann, "Über die Konstitution" (n. 1), 495–96.

then tried to reconstruct as an interpolated graph inferred from the data-points they could obtain from the plates. Hence, we have Kaufmann emphasizing that his plates were so sharp and clear that one could directly read off the dependency (see the quote in the Introduction), and stressing how close the fit was between the photographic curves and the interpolated graph. Bucherer equally well repeatedly emphasized the clarity and sharpness of his plates, and stressed, in response to Bestelmeyer's criticism, that the photographic curves could be taken to offer a direct representation—that is, with no interference of spurious rays—of the velocity-dependency of the electron's mass.

Guye and Lavanchy, on the other hand, did not aim for plates representing the whole velocity spectrum. For them, the velocity-dependency was rather to be inferred from many photographic plates together. Hence, they primarily emphasized the number of plates they had been able to produce, the number of traces each plate could contain, and the ease with which these traces could be produced and measured. In this way, two separate methods of visually achieving precision can be distinguished: Kaufmann, Bucherer, and Neumann attempted to achieve precision through quality, and each plate in itself therefore had epistemic value for them; Guye and Lavanchy, on the other hand, tried to obtain precision through quantity, and hence for them only the whole collection of plates together had epistemic value.

This difference in epistemic valuation not only concerned the photographic plates themselves but equally well the measurement values obtained from them. For Kaufmann, Bucherer, and Neumann, each individual photographic trace in itself was of possible value. This shows itself, for example, in the fact that they attempted as much as possible to publish all values obtained (even Neumann, who had obtained 55 plates, published all his values[107]). It can equally well be seen in how much attention they paid to comparisons with earlier obtained values: if a value performed well, it could be proclaimed as a new measurement standard to evaluate the adequacy of later experiments (as with Simon's or Bucherer's e/m_0-values, or in the case of Bucherer's appeal to the values obtained by Wolz and Classen). And it meant that one single problematic value could endanger the adequacy of a whole series of measurements: see for example Kaufmann's rejection of all high-velocity values in 1901, or Planck's claim that Kaufmann's results in general were suspect because some individual values entailed velocities surpassing that of light.

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[107] Neumann, "Die träge Masse" (n. 74), 558–59.

For Guye and Lavanchy, on the other hand, a single trace in itself had no real value. They did not deem it necessary, for example, nor even really feasible, to publish all the measurement values obtained. Nor did they focus as much on obtaining, or choosing, as precise an e/m_0-value as possible. Rather, they decided to just choose a value that was more or less between the values obtained in earlier experiments. Finally, they were not too worried about single values being problematic, either, since the amount of data obtained would prevent such individual values from being too influential. In this way, we see how the measurement data obtained were valued in the same way as the photographic plates from which they were inferred: while Kaufmann, Bucherer, and Neumann prioritized the quality of each individual value, Guye and Lavanchy focused on obtaining as much data as possible.

These differences in how precision was visualized and valued did not come out of nothing. Rather, as Kathryn Olesko argues extensively in her work on the history of precision measurement, scientists always evaluate the value of a precision measurement from within the local culture in which they were educated and in which they practice their trade: "[I]n and of themselves, precision measures, like other forms of quantification, do not necessarily prevail or command authority. Meaning is actively assigned to them from among the traditions of local cultures."[108] Such a culture, she continues, is to be understood as "a shared set of meanings, behavior, and guidelines for decision-making that characterize or accompany precision measurement. Judgments concerning the quality and significance of precision measures are made in the context of these cultures, using the tools available in it."[109] Similarly, Wilder argues that, as we have seen, Becquerel's visualizations of radioactive phenomena on photographic plates were influenced both by his imagination and by the nature of the radioactive and photographic materials at hand (see the quote in the Introduction). In what follows, I will argue, in line with Olesko's and Wilder's work, that the differences in epistemic valuation of plates and values in the case discussed here can equally well be traced back to different precision measurement cultures.

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[108] Kathryn Olesko, "Precision, Tolerance, and Consensus: Local Cultures in German and British Resistance Standards," in *Scientific Credibility and Technical Standards*, ed. Jed Z. Buchwald, 117–56 (Dordrecht: Kluwer Academic Publishers, 1996), 117.

[109] Olesko, "Precision" (n. 108), 127.

Different Precision Measurement Cultures

Following Wilder's claim quoted in the introduction, one element that can influence the photographic visualization of radiation phenomena is the specific radiating materials used. In the experiments discussed here as well, such material factors played a significant role. Kaufmann, Bucherer, and Neumann all used β-rays, since only these could attain the velocities believed to be required to make the velocity-dependency discernible. Guye and Lavanchy, on the other hand, worked with cathode rays, following earlier experiments that had shown that these rays as well could bring about the effect (see footnote 15; these earlier experiments had not attempted to capture the effect photographically). The importance of this difference lies in the fact that the type of radiation used significantly influenced the time required to produce meaningful traces on a photographic plate. Already in 1899, Rutherford had pointed out that with β-rays it took a long time, and this was indeed the case: Kaufmann required at least forty hours, and Bucherer up to sixty hours; Neumann was able to significantly reduce the time required but still needed between seven and sixteen hours. This was not the case with cathode rays: Guye and Lavanchy, as we have seen, needed only a few minutes to fill a photographic plate with traces.[110]

This difference in temporality entailed very different demands with regards to the experimental set-up. Kaufmann, Bucherer, and Neumann had to ensure that their set-up remained absolutely stable for the entire experimental run because the smallest fluctuations could disturb and blur the photographic plate produced. Hence, they constantly searched for ways to improve stability and to bring down the production time, which they mostly did by using stronger batteries, vacuum pumps, and magnets. This stability requirement also meant that dimensional determinations of all aspects of the set-up were of the utmost importance, since if these were not constantly measured and monitored during an experimental run, it was not possible to evaluate the set-up's stability (e.g., see the dispute between Bucherer and Bestelmeyer about the necessity of such dimensional measurements, Neumann's use of many high-precision measurement devices to carry out such measurements in response to criticisms

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[110] While they were the first to capture the velocity-dependency produced by cathode rays on photographic plates, it had been shown earlier that photographic plates capturing cathode rays could be produced fairly quickly: Bestelmeyer, in experiments from 1906 that were indirectly concerned with the velocity-dependency, had shown that it could be done in ninety minutes; see Bestelmeyer, "Spezifische Ladung" (n. 15), 439.

of Bucherer's set-up, or his use of colleagues to observe the set-up during an entire run). Hence, as Kaufmann put it, "the utmost attention was paid to achieve absolute immutability and exact measurability of all dimensions in question."[111]

Guye and Lavanchy's set-up, on the other hand, did not have to be absolutely stable: approximate field stability sufficed because the time required to produce a photographic trace was too short for fluctuations to have much influence. This, in turn, meant they did not have to focus so much on making all dimensions as measurable as possible, as there was no need to monitor them constantly. As a consequence, they could make their set-up flexible, by making the photographic plate and slit moveable via an easy-to-manipulate screw.

The difference in temporality, moreover, influenced not only the material set-up but equally well the produced results, that is, plates and data points. Kaufmann, Bucherer, and Neumann could produce only very few plates because it took so long to produce one. This, in turn, entailed that the number of data points to infer a velocity-dependency function from was limited, which made each individual dot that could be used very valuable. Hence, Kaufmann constantly tried to ensure that as many traces as possible could be used, for example, by redoing measurements, by having others redo them, and by weighing the quality of the plates, such that those plates that were of a lesser quality could also still count for something. Similarly, although Neumann had produced many plates that were not completely clear and sharp (29 out of 55, which were often partially blurred), he still published the measurement values he could obtain from them (see the reference in footnote 107). Guye and Lavanchy, on the other hand, had no problem in producing a significant number of photographic plates or data points because it took so little time to produce rows of photographic traces. Consequently, an individual dot on its own did not have that much value, and hence was not such an issue if some of the measurement values were erroneous.

As such, the nature of the radiating materials used—and in particular the time required for specific forms of radiation to leave behind traces on photographic plates—significantly shaped the experimental set-up used, as well as the number of plates and data points that could be produced. This already gives us quite an indication of how such material factors can influence the epistemic valuation of plates and the traces they contain. For Kaufmann, Bucherer, and Neumann, the production of one particular plate required quite

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[111] Kaufmann, "Über die Konstitution" (n. 1), 496.

some resources and effort, and they could produce only relatively few plates and traces. Hence, each plate in itself was quite valuable. Guye and Lavanchy, however, could produce many plates and traces with relatively little effort, and hence, the epistemic costs to produce a plate or a trace were low. This also meant that some plates and traces would be erroneous, and hence their individual epistemic value was also quite low. It was only when taken together that these plates could teach us something; thus it was only the collection of plates and traces that had epistemic value.

The nature of the radiation was not the only factor that influenced how the velocity-dependency was visualized, however. It cannot account, for example, for why Kaufmann, Bucherer, and Neumann represented the whole velocity spectrum in one curve, while Guye and Lavanchy saw no need for this. All scientists, it seems, could have chosen to visualize the phenomenon differently: Kaufmann, Bucherer, or Neumann could have produced plates containing rows of individual dots, and Guye and Lavanchy could have produced continuous photographic curves. These choices are rather to be accounted for in terms of the intellectual context in which they were working.

For Kaufmann, Bucherer, and Neumann, I will draw in particular on Olesko's work on the practice of precision measurement in different physics seminars in nineteenth-century Germany. During that period, Olesko argues, we can distinguish two different approaches. One, which she traces back to Franz Neumann's seminar in Königsberg, saw precision as achievable primarily through the application of mathematical methods, in particular the least squares method, to data obtained in any kind of measurement. The underlying idea was that these quantitative methods allowed one to eliminate errors in these data, in such a way that their certainty could be improved (see her 1991 book for an extensive discussion of what she describes as this "ethos of exactitude").[112] The other, which emerged in the seminars of Wilhelm Weber in Göttingen and Heinrich Gustav Magnus in Berlin, conceptualized precision as achievable primarily through the material improvement of instruments (for an extensive discussion of the Berlin seminar, see chapter 2 of Sjang ten Hagen's PhD dissertation[113]). Olesko summarizes this approach as follows:

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[112] Kathryn Olesko, *Physics as a Calling: Discipline and Practice in the Königsberg Seminar for Physics* (Ithaca, NY: Cornell University Press, 1991).

[113] Sjang ten Hagen, "History and Physics Entangled: Disciplinary Intersections in the Long Nineteenth Century" (Doctoral dissertation, Universiteit van Amsterdam 2021).

> Students achieved precision in the Göttingen exercises through the perfection of instruments, not the analysis of error (although they were certainly taught the method of least squares). So trials were thin and finite, and corrections for errors tended to be embodied in instruments. The conceptual vocabulary of precision centered on the instrument (rather than data), and the key term was reliability. They considered an instrument reliable when it had been modified to the point where the computation of constant errors was minimized. Hence, material perfection alone produced the fineness (*Feinheit*) of the data. Faith in the data having been thus secured, students felt confident in representing their results in idealized images that required interpolated points, such as graphs.[114]

Over time, Olesko has argued,[115] this Göttingen-Berlin approach to precision measurement became dominant within Germany, mainly through the success of Friedrich Kohlrausch's experimental physics textbooks, which he developed on the basis of the seminars he had organized in Göttingen.[116]

In his earlier, cathode ray work, Kaufmann sometimes referred to Kohlrausch's work (see footnote 10), so we know that he was at least familiar with it. Given the time period and context in which Kaufmann, Bucherer, and Neumann were trained and worked, and given the way in which they carried out and presented their results, we can assume, however, that it significantly shaped their practice, in particular if Olesko's characterization of the Göttingen-Berlin approach is correct, since the quote above aligns very well with how Kaufmann, Bucherer, and Neumann proceeded. They all attempted to exclude, as much as possible, errors in the identification and measurement of photographic traces by making the set-up that produced them as reliable as possible. This meant, on the one hand, that all its essential components had to remain stable over a long period of time. Hence, they were constantly searching for material improvements (better field sources, batteries, vacuum pumps, etc.). On the other hand, it also meant ensuring that all possible sources of error were excluded. Hence, we have Bestelmeyer putting so much emphasis

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[114] Kathryn Olesko, Unpublished manuscript translation of "Il seminari di ricercar e la fisica teorica," in *L'Ottocento*, vol. 7 of *Storia della scienza*, eds. Jed Z. Buchwald, Jed Z. et al. (Rome: Istitute della Enciclopedia Italiana, 2008), on 49–50.

[115] Kathryn Olesko, "Tacit Knowledge and School Formation," *Osiris* 8 (1993): 16–29; "The Foundations of a Canon: Kohlrausch's *Practical Physics*," in *Pedagogy and the Practice of Science: Historical and Contemporary Perspectives*, ed. David Kaiser (Cambridge, MA: MIT Press, 2005), 323–56.

[116] Friedrich Kohlrausch, *Leitfaden der praktischen Physik* (Leipzig: B. G. Teubner, 1870); *Lehrbuch der praktischen Physik* (Leipzig: B. G. Teubner, 1900).

on the possibility of spurious rays disturbing the photographic plates, or Neumann carrying out his experiments over the weekend to prevent a nearby tramway from interfering (while engaging others to observe the stability of the energy supply).

When such material reliability was achieved, the photographic curves were then expected to be as fine—that is, clear and sharp—as possible, and since all possible interferences had been excluded, they could then be taken as directly representing the velocity-dependency of the electron's mass: in a sense, these plates were then seen as directly providing graphs of the velocity-dependency curve, and the goal became to reproduce this curve as precisely as possible by means of theoretical models. This, again, also accounts for why individual plates were seen as so epistemically valuable: each of them, if produced in a reliable way, could offer a direct insight into the velocity-dependency. In this way, we come to see how the Göttingen-Berlin approach to precision measurement, as Olesko characterizes it, equally well shaped how Kaufmann, Bucherer, and Neumann attempted to produce photographic plates that allowed for precision.

This particular way of achieving precision photographically can be contrasted with one which, according to Wilder, originated with "Becquerel, who [...] created a very distinctive photographic method and used it in collaboration with a number of Parisian scientists, among them Paul Villard, Marie Curie and Henri-Alexandre Deslandres."[117] A particular characteristic of this approach was that it practiced photography in a very active and intervening way. As Wilder puts it, Becquerel "went beyond using photography as an instrument merely to detect the presence or absence of radioactive emissions. He used photographs as a tool for thinking—a method for understanding the physical nature of the rays by giving them visual form."[118] This experimental approach took on many forms: as Wilder points out, Becquerel "placed [radioactive] crystals directly in contact with the plates, wrapped the plates, sometimes in paper and sometimes in aluminum, put them in various containers to protect them from daylight, and allowed them to expose for varying length of time [...]; he used multiple photographic plates in a single experiment, observing then the effect on first one plate then another, and finally, he added direction to his images."[119] One consequence of this active

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[117] Wilder, *Photography and Science* (n. 7), 64.

[118] Wilder, "Visualizing Radiation" (n. 6), 352.

[119] Wilder, "Visualizing Radiation" (n. 6), 353.

and intervening approach was that, in this way, Becquerel obtained a significant amount of images: he produced "hundreds of what [he] called 'observations' (photographic, electric, phosphorescent, magnetic, and fluorescent) in a series of experiments on radiant bodies."[120]

As Karim has shown,[121] Guye's approach to the experimental study of cathode rays was influenced in particular by the work of Paul Villard.[122] As such, the claim that, together with Lavanchy, his approach to the production of photographic plates was inspired by the intellectual context surrounding Becquerel's work is a bit tentative, and there are certainly significant differences between them. Becquerel, according to Wilder, was interested primarily in the nature of radiation, and he used photographic plates in very varied ways in order to visualize that nature.[123] Hence, his work was only really constrained by his imagination (see the quote in the Introduction), especially because at the time there was no real research on radiation as of yet. Guye and Lavanchy, on the other hand, were working at a time when the behavior of radiation was already much better understood, and they moreover had a very specific aim—to visualize the velocity-dependency of the electron's mass as precisely as possible. Still, certain significant similarities appear in how Wilder characterizes Becquerel's approach. Guye and Lavanchy similarly designed their set-up in such a way to allow for a certain degree of manipulation and intervention: they made both the photographic plate and the slit plate moveable; they fitted many rows of traces on one single plate; and they tried out different photographic materials to see whether they made a difference (as did Becquerel[124]).[125] And, similarly to Becquerel, this provided them with an

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120. Wilder, "Visualizing Radiation" (n. 6), 349.

121. Karim, "Vérification expérimentale" (n. 87), 235.

122. For discussions of Villard's work, see Bruce Wheaton, *The Tiger and the Shark: Empirical Roots of Wave-Particle Dualism* (Cambridge, UK: Cambridge University Press, 1983), 53; Leif Gerward, "Paul Villard and His Discovery of Gamma Rays," *Physics in Perspective* 1 (1999): 367–83; Benoit Lelong, "Paul Villard, J.J. Thomson, and the Composition of Cathode Rays," in *Histories of the Electron: The Birth of Microphysics*, ed. Jed Z. Buchwald and Andrew Warwick (Cambridge, MA: MIT Press, 2001), 135–68.

123. Wilder, "Visualizing Radiation" (n. 6), 352.

124. Wilder, *Photography and Science* (n. 7), 59–60; "Visualizing Radiation" (n. 6), 353.

125. Guye and Lavanchy, "Vérification" (n. 86), 362. Guye and Lavanchy mention attempts with *Wellington, Bleues Lumière, Capella,* Italian plates, and *Violettes Lumière*. They eventually chose to work with *Capella*, Italian plates, and *Violettes Lumière* because these best allowed them to reduce production time. Kaufmann, Bucherer, and Neumann, on the other hand, never mention the photographic materials they employ: Kaufmann mentions only that they were produced by the *Plattenfabrik Dr. Schleussner* from Frankfurt (n. 1), 501.

abundance of photographic plates that they all used, although some were less qualitative than others (also true for Becquerel, who according to Wilder[126] was well aware of the limitations of the photographic method on its own, and therefore often combined it with other methods). These similarities and their reliance on the work of Villard (who worked in the same context as Becquerel, according to Wilder[127]), suggest, at least tentatively, that Guye and Lavanchy were working within the tradition of Becquerel, who "knew that a certain amount of work was necessary to make photographs appear at all[, which] gave him the power to control it and to inject a certain amount of imaginative practice."[128]

The above suggests that the specific way in which scientists attempted to visualize the velocity-dependency of the electron's mass on photographic plates was shaped by the intellectual context in which they were educated and in which they worked. Kaufmann, Bucherer, and Neumann worked within a context in which the goal was to produce experimental set-ups that functioned reliably, that is, with no outside interference. If such reliability was achieved, the plates could then be taken to offer a direct insight into the velocity-dependency, in the form of a photographic curve that corresponded to the sought after mathematical-theoretical expression. Guye and Lavanchy, on the other hand, worked within a context in which it was believed that the production of meaningful photographic plates always involved active human interventions. Hence, they did not aim for direct representations of a velocity-dependency graph but rather for traces that were clearly created but which allowed for simple measurements that, when combined with many other measurements, could then be used to infer the sought-after mathematical-theoretical expression.

CONCLUDING REMARKS: THE DEMISE OF THE PHOTOGRAPHIC METHOD

In this article I have argued that in the experiments concerning the velocity-dependency of the electron's mass carried out between 1901 and 1916 we can distinguish two approaches to the photographical visualization of the phenomenon: one that attempted to achieve precision through the production of

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[126] Wilder, "Visualizing Radiation" (n. 6), 358.

[127] Wilder, *Photography and Science* (n. 7), 64.

[128] Wilder, *Photography and Science* (n. 7), 364.

qualitative plates and traces, and one that aimed for precision through quantity, by producing as many plates and traces as possible. These two approaches, I have then argued, were shaped, on the one hand, by the nature of the radiating materials used—which was of significance for the time and effort required to produce individual traces and plates—and by the intellectual context in which the scientists involved were educated and in which they worked on the other. By taking these different factors into account, I then claimed, one can understand the very different ways in which the scientists involved attempted to visualize the velocity-dependency of the electron's mass as precisely as possible.[129]

This leaves open one question, however: how far can we take these photographic plates to offer actual insight into the velocity-dependency at issue? As we have seen in the introduction, not all scientists were convinced. Already in 1898, Rutherford pointed out that the method suffered from severe limitations, which, notwithstanding claims to the contrary, continued to rear their head in the experiments discussed: the duration of the experiments and the possibility of blurred photographic plates remained pressing issues. Becquerel as well believed that the method had its limitations, and that it was best combined with other methods (see footnote 126). And in 1908, Gilbert Lewis suggested that Kaufmann's plates were too unclear to infer anything (see the quote in the Introduction). These doubts received confirmation in 1938, when C. T. Zahn

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129. In a sense, one can say that the distinction between qualitative and quantitative approaches to precision sketched here is quite similar to the distinction, drawn by Lorraine Daston and Peter Galison in their book *Objectivity*, between mechanical objectivity and trained judgment. Kaufmann, Bucherer, and Neumann focused on improving the experimental set-up as much as possible in order to eradicate any kind of subjective influences, such that each photographic plate in itself would offer an objective depiction of the velocity-dependency. Guye and Lavanchy, on the other hand, allowed for certain interventions on the photographic plates in order to bring forth the velocity-dependency. It also displays similarities with the distinction drawn by Peter Galison, in his *Image and Logic*, between those physicists who tried to capture high-energy particles in the form of images, and those who tried to count and then combine them by logical means: whereas Kaufmann, Bucherer, and Neumann aimed for qualitative images, Guye and Lavanchy aimed for quantity and calculation. A more detailed comparison between the account sketched here and those of Daston and Galison, as well as with other studies of scientific photography (e.g. by Elizabeth Edwards, Omar Nasim, or Jennifer Tucker), is beyond the scope of the current article. Peter Galison, *Image and Logic: A Material Culture of Microphysics* (Chicago: University of Chicago Press, 1997); Lorraine Daston and Peter Galison, *Objectivity* (Princeton, NJ: Princeton University Press, 2007); Jennifer Tucker, *Nature Exposed* (Baltimore: Johns Hopkins University Press, 2006); Elizabeth Edwards, *The Camera as Historian* (Durham, NC: Duke University Press, 2012); Omar W. Nasim, *The Astronomer's Chair* (Cambridge, MA: MIT Press, 2021).

and A. H. Spees provided quite elaborate experimental arguments for it. They also deflected β-rays by means of electric and magnetic fields. They did not capture them on photographic plates, however: rather, they used "a Geiger counter as detector [to] eliminate the inconveniencies and the inaccuracies of the photographic method."[130] The Geiger counter served, more specifically, to measure radiation intensity given variations in the applied voltage or in the distance between source and plate. From this, they could then infer not only velocity-dependent changes in *e/m*, but equally well, whether the number of spurious rays would increase with velocity as well. This showed, they claimed, that such spurious rays were always present, and that they really manifested themselves in the high velocity range, from 0.7*c* onward. This, they claimed, invalidated all claims to precision in this range, and corroborated in particular Bestelmeyer's criticism of Bucherer's experiments:

> On the basis of the foregoing discussion it seems fair to say that the Bucherer-Neumann experiments actually proved very little, if anything more than the Kaufmann experiments, which indicated a large qualitative increase of mass with velocity. [. . .] [I]t seems remarkable that they were able to obtain lines at all for the higher velocities in consideration of the exceedingly poor performance of their velocity filters. What seems very surprising is the fact that Bestelmeyer actually raised objections along the lines of the present treatment, but still it was not discovered how very poor the resolution of the velocity filter really was.[131]

A similar claim was made by P. S. Faragó and L. Jánossy in 1957 in a review article covering all existing deflection experiments (now also including Guye and Lavanchy, whose work was not discussed by Zahn and Spees). They concluded that none of the experiments had provided results that could be taken to definitively favor the relativistic expression over that of Abraham.[132] This made them doubtful whether decisive experimental evidence for the relativistic velocity-dependency over Abraham's could be obtained at all by means of the photographic method. More promising results in this direction were rather to be found, they concluded, in studies of the relation between fine-structure splitting of spectral lines and variations in the electron's

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[130] C. T. Zahn and A. H. Spees, "An Improved Method for the Determination of the Specific Charge of Beta-Particles," *Physical Review* 35 (1938): 357–65, on 357.

[131] Zahn and Spees, "Critical Analysis" (n. 5), 519.

[132] P. S. Faragó and L. Jánossy, "Review of the Experimental Evidence for the Law of Variation of the Electron Mass with Velocity," *Il Nuovo Cimento* 5 (1957): 1411–36, on 1436.

charge-to-mass ratio during its motion in an atomic orbit, an idea first proposed by Karl Glitscher in 1917.[133] In this way, the photographic method more or less disappeared from the picture.

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[133] Karl Glitscher, "Spektroskopischer Vergleich zwischen der Theorien des starren und des deformierbaren Elektrons," *AdP* 357 (1917): 608–30.