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Philipp Lenard and the Photoelectric Effect, 1889–1911

By Bruce R. Wheaton*

I have by no means always been numbered among those who pluck the fruit; I have been repeatedly only one of those who planted or cared for the trees. . . .

*Lenard, Nobel lecture, 1905*¹

Philipp Lenard discovered in 1902 that the maximum velocity with which electrons leave a metal plate after it is illuminated with ultraviolet light is independent of the intensity of the light. He concluded that "in the process of emission the light plays only the role of triggering [the release of] a motion which already exists with full velocity inside the atoms of the body."² He felt that he had found a tool to probe the internal structure of the atom just when atomic theory was coming to the center of physicists' attention. Evidence from the production and absorption of photoelectrons suggested to him in 1903 that the atom is dynamic. The atomic volume, he thought, is filled not by a material substance, but by rapidly moving, electrically neutral subatomic units. By 1908, five years before the Bohr atom, Lenard was convinced that discrete spectral lines are emitted whenever an electron returns to a stable configuration in the atom. Lenard's early investigation of the photoelectric effect laid the foundation for several influential, if short-lived, ideas about atoms.

But Lenard's work on the photoeffect is usually cited in a different context today; his study is supposed to have been instrumental in the genesis of the light quantum hypothesis. It is frequently claimed that, following Lenard's work, the photoelectric effect constituted one of several "difficulties" for the wave theory of light.³ The claim would

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¹P. Lenard, "Ueber Kathodenstrahlen," in *Les Prix Nobel en 1905* (Stockholm, 1907), on p. 1 of the lecture.

²P. Lenard, "Ueber die lichtelektrische Wirkung," *Ann. Physik*, 8 (1902), 149–198, on 150.

³For examples, see R. H. Dicke and J. P. Wittke, *Introduction to Quantum Mechanics* (Reading, Mass., 1960), p. 12; R. M. Eisberg, *Fundamentals of Modern Physics* (New York, 1961), pp. 76–81; W. V. Houston and G. C. Phillips, *Principles of Quantum Theory* (Amsterdam, 1973), p. 12; A. L. Hughes and L. A. DuBridge, *Photoelectric Phenomena* (New York, 1932), p. 8; M. Jammer, *The Conceptual Development of Quantum Mechanics*

have greatly surprised Lenard. It is only since 1911 that the photoeffect has been interpreted as a transformation of light energy into electron kinetic energy. In 1902 Lenard concluded that the effect is a resonance phenomenon, but one in which the light contributes no energy to electrons. The light only selects which electrons are to be ejected from an atom. The velocity of a released electron is predetermined within the atom. Consequently a study of the velocity distribution of photoelectrons promised to shed light on atomic constitution.

Our understanding of Lenard's work is complicated by another historical distinction. In spite of his corroboration of J. J. Thomson's determination of the charge to mass ratio for the electron, Lenard did not believe that material electrons exist at all. He suggested that he had found evidence of free electricity: a "latent motion of the ether." In this view, Lenard reflected a current of German thought of the 1890s which laid greater emphasis on etherial explanations of electric discharge phenomena than on material interpretations. His was an experimentalist's expression of a viewpoint which led others to interpret matter itself as a reflection of discontinuities in the electromagnetic ether.⁴ But Lenard's commitment to an electromechanical interpretation arose in the context of a protracted debate about the nature of cathode rays. His appeal was motivated in part by an attempt to justify what had become an untenable position in the controversy.

Lenard's successful research on the photoelectric effect in 1902 was also partly based on his desire to corroborate an earlier claim. He first encountered the photoeffect at the start of his career, when he gave an unorthodox interpretation based on poorly controlled experiments. He soon proved that his explanation was specious, but he did not publish the proof. After losing three discoveries to others, he reinterpreted his explanation in terms of the new view of cathode rays. His reexamination at a time when most physicists had abandoned the photoeffect as unfruitful led him directly to his discoveries in 1902 and to his initial hypotheses about atoms.

For nine years the triggering hypothesis was the accepted explanation of the photoelectric effect. It enabled physicists to avoid the serious difficulties which obstructed formulation of a consistent

(New York, 1966), p. 35; R. B. Leighton, *Principles of Modern Physics* (New York, 1959), pp. 67-68; A. Messiah, *Quantum Mechanics*, trans. G. M. Temmer (Amsterdam, 1961), I, 11-13, 41; F. K. Richtmyer, E. H. Kennard, and J. N. Cooper, *Introduction to Modern Physics*, 6th ed. (New York, 1969), pp. 162-164.

⁴See R. McCormach, "H. A. Lorentz and the Electromagnetic View of Nature," *Isis*, 61 (1970), 459-497.

mechanism for the absorption of classical electromagnetic waves. The light quantum proposed by Einstein to answer more general issues incidentally offered another explanation of the photoeffect. But other physicists preferred the triggering hypothesis. After the triggering explanation failed in 1911, there was no adequate theory of the photoelectric effect. For another decade, the light quantum was considered an unwarranted rejection of the thoroughly verified classical wave theory of light.

This paper describes the context, substance, and influence of Lenard's investigation of the photoelectric effect. It presents the motivations and interprets the technical basis for his proposal of the triggering hypothesis. The issues that brought him to this study and the motivations for some of his conclusions are not marked by the ideals of dispassion and objectivity that are frequently given as prerequisites for successful empirical study in physics. Despite Lenard's deserved reputation as a good experimental physicist, his theoretical hypotheses suffered repeated rejection. The experiences detailed here affecting his early career may have contributed to the personality traits that induced this Nobel prize winning physicist to become, late in his life, the leading physicist spokesman for the National Socialist cause in Germany.

1. COMMITMENTS: THE PHOTOELECTRIC EFFECT AND CATHODE RAYS, 1889–1895

By 1889, the photoelectric effect had assumed a special significance. Discovered two years before as a by-product of Heinrich Hertz's experimental demonstration of electromagnetic waves, the photoeffect seemed to be a direct transformation of light into electricity.⁵ It was a popular research topic.⁶ Not just German, but Italian and Russian physicists made important contributions to its study.⁷ These physicists had established that illuminating a metal plate with ultraviolet

⁵H. Hertz, "Ueber einen Einfluss des ultravioletten Lichtes auf die elektrische Entladung," *Ann. Physik*, 31 (1887), 983–1000.

⁶An average of sixteen articles on the photoelectric effect appeared per year in the period 1888–1890, seven articles per year until 1898. E. R. von Schweidler, "Über die lichtelektrischen Erscheinungen," *Sitzbr. math. naturwiss. Kl. Akad. Wiss. Wien*, 107:IIa (1898), 881–909.

⁷The major contributors were Wilhelm Hallwachs, Augusto Righi, and Alexandr Stoletov. For a detailed treatment of their work see my study "The Photoelectric Effect and the Origin of the Quantum Theory of Free Radiation" (unpublished M.A. thesis, University of California at Berkeley, 1971).

light initiates a flow of negatively charged particles from the plate.⁸ This occurs whether the plate is initially uncharged or charged with negative electricity. The nature of the photocurrent particles was unclear. Most investigators assumed that the light encourages molecular dissociation. They thought that molecules of ambient gas are separated into their charged atomic constituents after contacting the plate and the negatively charged products are subsequently repelled.⁹

Lenard never did accept this explanation. Many years later he recalled the strong impression that the photoelectric effect had on him when he encountered it while he was assistant to Georg Quincke in Heidelberg. Dissatisfied with Quincke's tendency to do refined experiments on established topics, Lenard took the new phenomenon to be a "comforting sign that a physicist need not restrict himself to subjects which by contemporary standards are already known and explained."¹⁰ In the spring of 1889, three years after receiving his doctorate, Lenard performed some simple experiments on the photoeffect with the future astronomer Max Wolf. They based their study on investigations by a secondary school teacher, Robert Nahrwold, who had concluded that it was "highly probable that a gas cannot be statically electrified."¹¹ To Lenard, Nahrwold's results indicated that gases can never be electrically charged. "No particle [of a gas] can take on a quantity of electricity," he claimed. This was as true of polyatomic gas molecules as it was of their dissociated atoms. Electrical discharges through gases were to be attributed to charged "dust," small particles from the electrodes or from the glass walls of the tube. "Dust can be electrified," he asserted, "a gas cannot."¹²

The elementary experiments that Lenard and Wolf cited in support of their claim were easily misinterpreted. Metal plates exposed to strong ultraviolet irradiation appeared "roughened" on close exam-

⁸W. Hallwachs, "Ueber den Einfluss des Lichtes auf elektrostatich geladene Körper," *Ann. Physik*, 33 (1887), 301–312. A Righi, "Di alcuni nuovi fenomeni elettrici provocati dalle radiazioni, Nota II e III," *Rendiconti R. Accad. Lincei*, 4 (1888), 498, 578–580.

⁹The investigations which led to this view will be discussed in my study "The Discovery of the Photoelectric Effect: Anatomy of Perception," in preparation.

¹⁰P. Lenard, "Erinnerungen eines Naturforschers, der Kaiserreich, Judenherrschaft, und Hitler erlebt hat" (unpublished manuscript, 1943), p. 28. A microfilm of the manuscript has been deposited at the Office for History of Science and Technology, University of California, Berkeley.

¹¹R. Nahrwold, "Ueber Luftpolectricität," *Ann. Physik*, 31 (1887), 448–473, on 469, 473. It became clear, after Lenard and Wolf's citation, that Nahrwold made no claim about charges on individual gas molecules. See his "Bemerkung zu der Abhandlung des Hrn. F. Narr: 'Über die Leitung der Electricität durch Gase'," *Ann. Physik*, 33 (1888), 170–172.

¹²P. Lenard and M. Wolf, "Zerstäuben der Körper durch das ultraviolette Licht," *Ann. Physik*, 37 (1889), 443–456, on 444.

ination; a jet of steam became opaque, as expected, by condensation on "dust" particles whenever the electrical discharge occurred. When these experiments were criticized the following year, Lenard devised a clever experiment.¹³ He illuminated a sodium amalgam cathode until a predetermined charge passed to a platinum wire anode. Were the charge carried by particles from the cathode, the quantity of sodium deposited should have been sufficient to be detected spectroscopically. Lenard heated the wire to incandescence. To his surprise he found no sodium lines in the spectrum.¹⁴

Lenard had several reasons not to make this result public. He agreed with prevailing opinion that the photocurrent carriers are charged particles of some kind. It seemed now that they could only be particles of the gas. By the time he was in a position to carry the investigation further, his result contradicted more than just his first explanation of the photoeffect. He had become assistant to Heinrich Hertz in Bonn and under his influence had begun to study the properties of cathode rays. He realized quickly that the result of his photoelectric test raised doubts about the hypothesis which formed the basis of Hertz's and his own views on the nature of cathode rays.

Cathode rays are invisible products of electrical discharge in a partial vacuum which make their presence known by exciting fluorescence in the glass walls of the discharge tube. First described by Julius Plücker in 1858, they were named "cathode rays" [*Kathodenstrahlen*] by Eugen Goldstein some twenty years later.¹⁵ They seemed to come exclusively from the negative electrode. Early investigations by

¹³Lenard performed this experiment in 1890–1891, but he first revealed the date in the annotated second edition of his Nobel lecture *Ueber Kathodenstrahlen* (Berlin, 1920), p. 39n. The test was stimulated by R. von Helmholtz and F. Richarz, "Ueber die Einwirkung chemischer und elektrischer Prozesse auf den Dampfstrahl und über die Dissociation der Gase, insbesondere des Sauerstoffs," *Ann. Physik*, 40 (1890), 161–202, especially 187, where the authors show that condensation nuclei can be produced by chemical reactions.

¹⁴In his "Erinnerungen," *op. cit.* (note 10), p. 33, Lenard recalled that he found in 1890 that the dispersion was not necessarily due to ultraviolet light. He had drawn this conclusion from spectroscopic tests performed on sodium and copper cathodes between December 1890 and February 1891. See P. Lenard, *Wissenschaftliche Abhandlungen*, Ludwig Wesch, ed. (Leipzig, 1944), 3, 238n; and P. Lenard and C. Ramsauer, "Über die Wirkung sehr kurzwelligen ultravioletten Lichtes auf Gase und über eine sehr reiche Quelle dieses Lichtes. IV. Teil. Über die Nebelkernbildung durch Licht in der Erdatmosphäre und in anderen Gasen, und über Ozonbildung," *Sitzbr. Heidelberg Akad. Wiss., math. naturwiss. Kl.*, 2a (1911), section 16, 25n.

¹⁵J. Plücker, "Ueber die Einwirkung des Magneten auf die elektrischen Entladungen in verdünnten Gasen," *Ann. Physik*, 103 (1858), 88–106. E. Goldstein, "Über die Entladung der Elektrizität in verdünnten Gasen," *Monatsberichte Akad. Wiss. Berlin* (1880), pp. 82–124.

William Crookes showed that cathode rays are bent by a magnet, exert forces on an object in their path, and, unlike isotropically emitted light, follow trajectories which remain perpendicular to the cathode surface.¹⁶ Crookes concluded from these properties that the rays are charged "projected material molecules" and in this view he was followed by most English physicists. In Germany the predominant, although not exclusive, view was that cathode rays are vibrations in the ether of short wavelength.¹⁷ The German physicists' explanation followed from their assumption that only ether waves can stimulate fluorescence. Hertz had contributed strong evidence for the ether wave hypothesis in 1883 when he had found it impossible to deflect cathode rays by an electrostatic field. He also showed that the course of the electric discharge and the path of the cathode rays are not necessarily related to one another.¹⁸

Lenard accepted the German hypothesis about cathode rays. As a student he had tried to pass the rays through a quartz window known to be transparent to ultraviolet light.¹⁹ Shortly after he became Hertz's assistant in 1891, he witnessed Hertz's discovery that cathode rays can excite fluorescence even after passing through thin metal foils.²⁰ This seemed the capstone of the German interpretation. One could imagine that thin foil is transparent to the cathode-ray "light" as glass is transparent to visible light or as insulators are transparent to low frequency electromagnetic radiation. It was considerably more difficult to imagine that material molecules can pass through solids.

Lenard suspected and was soon convinced that the photoelectric effect is initiated by cathode rays. He recognized almost immediately a new significance of his sodium photoelectric experiment. If the photocurrent is carried by cathode rays, his experimental result could be explained in only two ways: one either had to assume that electrically neutral cathode rays can stimulate charges on gas molecules or that the cathode rays themselves are charged particles. Both hypoth-

¹⁶W. Crookes, "Bakerian Lecture on the Illumination of Lines of Molecular Pressure and the Trajectories of Molecules," *Phil. Trans. Roy. Soc. London*, 170 (1879), 135-164.

¹⁷The German view was not accepted by Hermann von Helmholtz, Gustav Wiedemann, or Emil Wiechert. For reviews, see G. Wiedemann, *Die Lehre von der Elektrizität* (Braunschweig, 1885), vol. 4, part 1, pp. 405-600; O. Lehmann, *Die elektrischen Lichterscheinungen oder Entladungen* (Halle, 1898), pp. 518-547; and A. Schuster, *The Progress of Physics During 33 Years (1875-1908)* (Cambridge, 1911), pp. 52-67.

¹⁸H. Hertz, "Versuche über die Glimmentladung," *Ann. Physik*, 19 (1883), 782-816, especially 809-815.

¹⁹Lenard, *op. cit.* (note 1), p. 3; (note 10), p. 45.

²⁰H. Hertz, "Ueber den Durchgang der Kathodenstrahlen durch dünne Metallschichten," *Ann. Physik*, 45 (1892), 28-32. See Lenard, *op. cit.* (note 10), pp. 28-31, for details of his early attraction to Hertz and to the photoeffect.

eses were incompatible with the position Lenard had taken. He kept the result of the sodium experiment to himself for close to a decade.

At Bonn, Lenard investigated the passage of cathode rays through thin metal foil. In 1893 he found that the impinging cathode rays make the air behind the foil conduct electricity. He thought that the incident rays are analogous to light, and in seeking the source of induced conductivity he applied his knowledge of the photoeffect. The cathode-ray light, in passing through the foil, triggers the emission of charged particles and this makes the surrounding air conduct electricity. This interpretation supported his hypothesis that the electric current in the pure photoeffect is induced by the emission of cathode rays. In 1894 he tried to detect cathode rays during the photo-discharge by means of a fluorescent screen, but he failed.²¹

The primary goal of Lenard's research was to measure the properties of the cathode rays. Between 1892 and 1898 he used the transmission technique to study cathode rays in hitherto unattainably pure beams. Cathode rays require a small gas pressure for production. Until Lenard's experiments the study of cathode beam behavior in high vacuum was, therefore, not possible. This was the reason for Hertz's failure in 1883 to observe electrostatic deflection of the rays. But Lenard built discharge tubes containing a reinforced aluminum foil "window" through which the rays could pass completely out of the tube and escape the stringent conditions required for their production.²² Among other properties he charted the rate at which these "external" cathode rays are absorbed in various materials by exposing photographic plates, some completely wrapped in opaque paper, to the emanation from the metal window.²³ Lenard eventually received many prizes including the fifth Nobel prize in physics for this research.

2. DISAPPOINTMENTS: X RAYS AND CATHODE RAYS, 1895–1897

In retrospect it is clear that some of the effects Lenard attributed to cathode rays were caused by the X rays his tube produced. Indeed Lenard provided more than just the techniques which Wilhelm Con-

²¹Lenard, *op. cit.* (note 1), p. 18.

²²P. Lenard, "Ueber Kathodenstrahlen in Gasen von atmosphärischem Druck und im äussersten Vakuum," *Ann. Physik*, 51 (1894), 225–268.

²³P. Lenard, "Ueber die Absorption der Kathodenstrahlen," *Ann. Physik*, 56 (1895), 255–275.

rad Röntgen employed in his investigations of cathode rays. One of the discharge tubes that Röntgen was using when he discovered X rays in the fall of 1895 was designed by Lenard. The tube was distinguished by a platinum extension, on the end of which was fixed the aluminum window.²⁴ Lenard discovered that the conductivity induced in air outside the tube was significantly strengthened when the cathode rays inside were directed at the platinum. But his own tube had failed early in use and he had not replaced it.²⁵ When Röntgen requested information from Lenard about appropriate window foil he also ordered a tube built to Lenard's specifications from the Braunschweig glassblower Müller-Unkel. It was sent to Röntgen at Würzburg, where he reported its successful operation in June 1894.²⁶ Röntgen's discovery of X rays the following year was made possible in part by his unfamiliarity with the behavior "expected" of discharge tubes.²⁷

Conscious of Lenard's potential claim of priority, Röntgen was careful to show that X rays have properties that are both qualitatively and quantitatively different from those of Lenard's "external" cathode rays. Like cathode rays, X rays cannot be refracted or reflected; unlike cathode rays, they are not deflected by a magnet. Röntgen also showed that X rays are absorbed by matter in a different

²⁴Lenard described the special tube in *op. cit.* (note 22), p. 228n.

²⁵Much later Lenard blamed Hertz for retarding research which might have led him to X rays. See Lenard, *op. cit.* (note 13), p. 83n; (note 14), 3, 65n; and (note 10), pp. 45, 47–48. Hertz's sickbed charge with editorial responsibilities for his *Principles of Mechanics* did slow Lenard's research, but most of Lenard's later complaints are incompatible with his contemporary opinion. See Lenard to Max Wolf, 27 January 1894, *Physikalische Blätter*, 13 (1957), 567–569.

²⁶Wilhelm Röntgen to Ludwig Zehnder, 21 June 1894. Published in L. Zehnder, W. C. Röntgen. *Briefe an L. Zehnder* (Zürich, 1935), pp. 28–29. Among the few documents that Röntgen kept were his letter of 4 May 1894 ordering the tube and the invoice of its receipt. For these and Röntgen's letters to Lenard, dated 4 May 1894 and 8 May 1894, see J. Stark, "Zur Geschichte der Entdeckung der Röntgenstrahlen," *Phys. Zs.*, 36 (1935), 280–283. Lenard's reply to Röntgen, dated 7 May 1894, has been published in Etter, "Some Historical Data Relating to the Discovery of the Roentgen Rays," *Am. J. Roentgenology and Radium Therapy*, 56 (1946), 220–231. Lenard was convinced that Röntgen had used this tube in making his discovery. See Lenard, *op. cit.* (note 10), pp. 56–57, 74–75; and (note 14), 3, 5n, 65n, 69n. Röntgen's biographer agreed that it was possible but thought it unimportant. See O. Glasser, "What Kind of Tube Did Röntgen Use When He Discovered the X-Ray?" *Radiology*, 27 (1936), 138–140.

²⁷W. C. Röntgen, "Über eine neue Art von Strahlen," *Sitzbr. phys. med. Gesell., Würzburg* (1895), pp. 132–141; reprinted in *Ann. Physik*, 64 (1898), 1–11. Thomson and Whittaker told of a physicist who realized that his discharge tube fogged his photographic plates and solved the problem by storing them elsewhere. J. J. Thomson, *Recollections and Reflections* (London, 1936), p. 402n; E. T. Whittaker, *A History of the Theories of Aether and Electricity*, 1 (London, 1951), 358n. See also A. W. Goodspeed and W. N. Jennings, "The Röntgen Phenomena. A Few Early Results Obtained at the University of Pennsylvania," *Science*, 3 (1896), 394–396.

way than are the cathode rays. The decrease in X-ray intensity is not strictly proportional to the mass traversed, as Lenard had proven it is for cathode rays.²⁸

Lenard had already noted that cathode rays produced at high potentials behave like Röntgen's X rays. He interpreted the distinguishing characteristics purely as differences of degree. Because he was convinced that both cathode rays and X rays were electromagnetic waves, he thought that Röntgen had isolated only some extreme properties of the ether wave outside the tube that Lenard had already described. X rays were, for Lenard, simply especially "hard" cathode rays, that is, cathode rays with a velocity close to, possibly equal to, that of light. He saw his own painstaking investigations as evidence of prior discovery; Röntgen's dramatic photographs seemed little more than a technical refinement.

Röntgen's "new kind of ray" which could pass through matter brought him great fame. As Lenard noted in his letters to Röntgen in the spring of 1897, it also drew attention to Lenard's work.²⁹ At first, scientists largely agreed with Lenard's claims to substantial credit for the discovery. The Vienna Academy awarded half of its Baumgartner Prize for 1896 to Lenard, the other half to Röntgen. The Royal Society awarded duplicate Rumford Medals to Lenard and Röntgen for the discovery of "phenomena which occur outside" discharge tubes. The Paris Academy awarded the 1897 La Caze prize in physics to Lenard and that in physiology to Röntgen.³⁰ The first Nobel prize for physics was awarded to Röntgen in 1901, but the nominating committee had recommended that it be shared with Lenard.³¹

²⁸Lenard, *op. cit.* (note 23), pp. 266–270; and Röntgen, *op. cit.* (note 27), p. 3. In his manuscript, Röntgen had first written something other than "Röhre" (tube) to describe the source of the fluorescence which led to his discovery of X rays. The deleted words have been read as "Lenard Apparat," but a more realistic interpretation is "Entladu Apparat" where Röntgen first decided to delete "Entladungs" before completing it, tried "Apparat" by itself, and finally settled on "Röhre." Only a photograph of the first page of the manuscript, the only page Röntgen retained, survived World War II. It is held at the Deutsches Röntgen Museum, Remscheid-Lennep; a reproduction may be found in Herbert S. Klickstein, *Wilhelm Conrad Röntgen on a New Kind of Rays: A Bibliographical Study* ([St. Louis], 1966), p. 23.

²⁹Lenard to Röntgen, 7 May 1894, 21 May 1897, and 23 June 1899; Röntgen to Lenard, 24 April 1897. See Etter, *op. cit.* (note 26).

³⁰For the Baumgartner Prize see *Sitzbr. math. naturwiss. Kl. Akad. Wiss. Wien*, 105:IIa (1896), 501. For the Rumford medal see *Proc. Roy. Soc. London*, 60 (1897), 313–314, where a tactfully worded announcement evades the issue of priority. The results of the Paris Academy deliberations are published in *Comptes rendus*, 126 (1898), 77–78 and 114–115. Röntgen's debt to Lenard is acknowledged by Röntgen's former assistant, friend, and biographer Ludwig Zehnder in *Wilhelm Conrad Röntgen, Professor of Physics 1845–1923* (Neuchâtel, 1930), pp. 10–11.

³¹Folke Knutson, "Röntgen and the Nobel Prize," *Acta Radiologica (Diagnosis)*, 15 (1974), 465–473.

But Lenard's claims were soon discounted, particularly after 1897, when strong evidence was found that conflicted with his interpretation of cathode rays. British physicists, always suspicious of Lenard's view of cathode rays, were the first to question his claim to the discovery of X rays. G. G. Stokes summed up the opinion of many when he remarked, "Lenard may have had the rays in his brain, but Röntgen got them into other people's bones."³² That the Swedish Academy chose to disregard its committee's suggestion that Lenard share the Nobel prize with Röntgen indicates that by 1901 Lenard's claim was no longer accepted on the continent either.

The discovery of X rays raised hopes that the nature of their parent cathode rays might soon be clarified. Lenard was an acknowledged expert on cathode rays and was invited by the British Association for the Advancement of Science to attend its sixty-sixth meeting in 1896.³³ The president of the physics section for that meeting was J. J. Thomson, who supported the charged-particle hypothesis of cathode rays. Both there and at the equivalent German meeting six days later in Frankfurt am Main, Lenard suggested that X rays were no more than especially "hard" cathode rays, those virtually undeflected by a magnetic field.³⁴ Cathode rays and X rays were both ether waves to Lenard. In his presidential address Thomson pointed out that Lenard's interpretation conflicted with Jean Perrin's recent demonstration that cathode rays, unlike X rays, transport negative charge.³⁵ Lenard, convinced that meaningful research on cathode rays could only be carried out in high vacuum, thought Perrin's results inconclusive and did not respond.

By April 1897 Thomson had found that an electrostatic field deflects cathode rays.³⁶ Hertz's failure in the same test had been due to a premature discharge of the deflecting potential in his less than perfect vacuum. Thomson's experiment established the British hypothesis of cathode rays, and Thomson soon showed that the beam exhibits a constant mass to charge ratio the value of which is independent of

³²Arthur Schuster, *Biographical Fragments* (London, 1932), p. 242.

³³Thomson, *op. cit.* (note 27), p. 408. The invitation came from Lord Kelvin and Oliver Lodge; see Lenard, *op. cit.* (note 10), pp. 89-93.

³⁴P. Lenard, "On Cathode Rays and Their Probable Connection with Röntgen Rays," *Rep. Brit. Assn. Adv. Science* (1896), pp. 709-710; "Ueber die Eigenschaften der Kathodenstrahlen verschiedener Ablenkbarkeit," *Verh. Gesell. Deut. Naturf. Ärzte, 1896* (Leipzig, 1897), part 2, first half, pp. 69-70.

³⁵J. J. Thomson, "Presidential Address," *Rep. Brit. Assn. Adv. Science* (1896), pp. 699-706, on p. 702. J. Perrin, "Nouvelles propriétés des rayons cathodiques," *Comptes rendus*, 121 (1895), 1130-1134.

³⁶J. J. Thomson, "Cathode Rays" (30 April 1897), *Proc. Roy. Inst.*, 15 (1899), 419-432.

both the gas in the tube and the material of the cathode.³⁷ The ratio was smaller than that of the positive hydrogen ion by a factor of 10^3 , and Thomson concluded, partly on the basis of Lenard's absorption data, that the "corpuscles" which form the cathode beam are smaller than any known atom.

Thomson's result was a shattering blow to the ideas that had guided Lenard's successful research program. The isolation of the electron seemed to remove any possibility that cathode rays were, as Lenard had been putting it, "processes in the ether." Moreover it destroyed the basis of Lenard's claim to the discovery of X rays. It was no longer possible to equate X rays with cathode rays because virtually all physicists, Lenard included, agreed that X rays are uncharged electromagnetic disturbances.³⁸ Lenard responded with a compromise. The cathode rays could still be ethereal if he assumed that they were hitherto unobserved units of pure electricity. Their mass derived from their electromagnetic, rather than from their mechanical, properties. Lenard duplicated Thomson's experiment in what he considered to be the purer form in high vacuum and he obtained virtually the same numerical result. "In every respect," he said, "the rays behaved like moving masses carrying negative charge." But he interpreted the result in a wholly different way: "Here one has evidence of the existence of individual pieces of the ether, hitherto unobserved, which move individually, possess mass (inertia), and seem to be identical to the carriers of electric charge."³⁹

It was with the benefit of his new understanding of cathode rays that Lenard returned to the photoelectric effect. For eighteen months after his response to Thomson he published nothing. He had been appointed full professor at the University of Kiel in 1898 and was supervising the construction of a new physical institute. During this interval he encountered the little known result of the Italian physicist Augusto Righi: as gas pressure in the tube decreases, the paths of the

³⁷J. J. Thomson, "Cathode Rays," *Phil. Mag.*, 44 (1897), 293-316. The original value for m/e was 1.5×10^{-7} gm/emu.

³⁸This is not to suggest that there was unanimity about the form of the disturbance. These issues are discussed in my dissertation *On the Nature of X and Gamma Rays: Attitudes toward Localization of Energy in the "New Radiations," 1896-1922* (Princeton, in preparation).

³⁹P. Lenard, "Ueber die electrostatischen Eigenschaften der Kathodenstrahlen," *Ann. Physik*, 64 (1897), 279-289, on 279. Eight years later he elaborated: "We have no evidence that (negative) electricity is a particular material possessing inertia; it only appears to us as a state, just that state of the ether that, following Faraday, Maxwell, and Hertz, we called the electric force field in the vicinity of electrified bodies." He described cathode rays as a "latent motion of the ether" and "the perhaps empty and purely geometric centers of electric forces." *Op. cit.* (note 1), p. 16.

photo-discharge particles deviate from the electric field lines running from cathode to anode. For very low pressures the particles follow straight trajectories normal to the surface of the cathode regardless of the direction of the imposed field.⁴⁰ To one as familiar with the identical behavior of cathode rays as Lenard, the conclusion must have seemed inescapable. Now that it had been shown that cathode rays carry negative charge, Lenard could simply equate the photocurrent "particles" with the cathode rays. Ultraviolet light stimulates the emission of cathode rays directly from the metal. If the vacuum is good enough, the cathode rays carry the discharge completely across the tube. Lenard's new concept of cathode rays allowed him to salvage his earlier interpretation of the photoeffect. By identifying the charged "dust" as cathode rays he upheld his claim that charged gas atoms do not carry the photocurrent.

3. ACCOMMODATION: THE PHOTOELECTRIC EFFECT, 1898–1902

In October 1899, Lenard finished his careful experimental justification of "The Production of Cathode Rays by Ultraviolet Light."⁴¹ First he revealed the result of the spectroscopic examination he had done eight years before: particles from the cathode do *not* carry the discharge. Next he reported that "all characteristic effects of ultraviolet light known in air persist at the highest vacuum," implying that the photocurrent does not depend on the gas in the tube.⁴² Finally, by assuming a negligible initial velocity for the electrons or "quanta," as he called them, he could measure the charge to mass ratio by magnetic deflection of the beam.⁴³ The ratio remained constant as the accelerating potential between the electrodes increased twentyfold.

⁴⁰A. Righi, "Sulla convezione fotoelettrica e su altri fenomi elettrici nell'aria rarefatta," *Memorie della Reale Accademia della Scienze dell'istituto di Bologna*, 1 (1890), 85–114.

⁴¹P. Lenard, "Erzeugung von Kathodenstrahlen durch ultraviolettes Licht," *Sitzbr. math. naturwiss. Kl. Akad. Wiss. Wien*, 108:IIa (1899), 1649–1666, presented 19 October 1899 and reprinted the following year in *Ann. Physik*, 2 (1900), 359–375.

⁴²*Ibid.*, p. 1652. Lenard was evidently unaware of Stoletov's early demonstration that the photocurrent does not drop completely to zero for very low pressures; "Sur les courants actino-électriques dans l'air raréfié," *Journ. physique théorique et appliquée*, 9 (1890), 468–473.

⁴³Lenard's "quantum" was a "unit of pure electricity" and must not be confused with Planck's "quantum of action." In current parlance Lenard's quantum is an electron. But Lenard had strong doubts that cathode rays were particles in the ordinary sense of the word; he continued, for many years, to insist on the term "Quanten."

Its value was tolerably close to that found for ordinary cathode rays. In fact, he remarked, it was exactly as if cathode rays were passing through the tube; yet he found it impossible to excite cathode rays in that high a vacuum by the electrode potential alone. When he introduced enough air in the tube that ordinary cathode rays appeared, he measured essentially the same charge to mass ratio.

Lenard also explained why others were convinced that gas atoms carry the photo discharge. In the presence of gas, the cathode rays emitted from the plate will be "absorbed" and the gas, in fact, becomes the transporter of charge. Only at high vacuum is the photoelectric discharge carried by pure cathode rays. Lenard had never accepted the hypothesis that gas atoms carry the photoelectric discharge; he probed more deeply where others had been content with the gas hypothesis. His efforts were now rewarded by a partial vindication of his earlier ideas.

Only a few weeks before Lenard presented his paper to the Vienna Academy in 1889 he found that Thomson shared his view that the photo discharge is carried by cathode rays.⁴⁴ Once again Lenard's work was anticipated by another. Thomson had found that the photoelectric effect allowed a simultaneous determination of the charge to mass ratio and of the charge of the electron. The cathode-ray beam that he had examined in 1897 allowed only the ratio to be measured. A different source of electrons, the ionization produced in a gas by X rays, permitted him to determine the charge by vapor condensation; but because the resulting charged particles did not form a beam, he could not determine the ratio.⁴⁵ In the spring of 1899 he recognized that the photoeffect would allow both determinations.⁴⁶ The ratio was equivalent to that of the cathode rays. The value of the charge, -6.5×10^{-10} esu, agreed with that found for the ions produced by X rays, for the positive hydrogen ion from electrolysis, and for the charge of the electron derived by Lorentz from Zeeman

⁴⁴J. J. Thomson, "Über die Masse der Träger der negativen Electricisierung in Gasen von niederen Drucken," *Phys. Zs.*, 1 (1889), 20-22. It was uncharacteristic of Thomson to publish in German journals, particularly a first announcement of his results. He was likely aware of the direction of Lenard's research. Lenard later claimed that Thomson's work followed his own. P. Lenard and A. Becker, "Lichtelektrische Wirkung," in *Handbuch der Experimentalphysik*, W. Wien and F. Harms, eds. (Leipzig, 1928), 23, part 2, 1041-1514 and 1533-1544, on 1050n; and Lenard, *op. cit.* (note 14), 3, 237n.

⁴⁵J. J. Thomson, "On the Charge of Electricity Carried by the Ions Produced by Röntgen Rays," *Phil. Mag.*, 46 (1898), 528-545.

⁴⁶Thomson first revealed his success in a letter to Rutherford in July 1899; see A. S. Eve, *Rutherford* (New York, 1939), p. 68.

splitting and from data on optical dispersion.⁴⁷ This confirmed Thomson's hypothesis about the fundamental nature of the electron. He estimated the size of the electron and explained ionization as the loss of atomic electrons.⁴⁸

But the photoeffect was not Thomson's main interest. He continued to use a hypothetical mechanism he had proposed in 1893 according to which the electrons come from a polarized gas layer adjacent to the cathode.⁴⁹ It was not important to him whether the electrons came from gas atoms or from cathode atoms. His findings made the issue irrelevant: electrons from any atom, gas or cathode, are the same. To Lenard, however, the question was of great significance. He had discovered that the emission proceeds in the complete absence of the gas. Therefore the electrons must come from the cathode. He realized further that these cathode rays are of significantly lower velocity than any previously isolated, and this opened the possibility of new cathode-ray studies of fundamental importance.

In the course of his investigation, Lenard puzzled over the fact that one can measure a small photocurrent passing from a *positively* charged plate as long as the potential does not exceed a value characteristic of the metal.⁵⁰ Even when the external potential acts to accelerate cathode-ray electrons back to the cathode, some of them still manage to pass to the anode. He found that the current saturates both at high accelerating and high decelerating potentials. Negative charge flows away from the plate until the characteristic positive potential is reached. If the initial potential of the plate is decreased, there is less resistance to the outflow of electrons so that the initial current is greater. The initial current becomes even greater when the potential of the cathode plate is reduced to values negative with respect to the anode. Electrons are then accelerated away from the plate. But below a second threshold potential, also characteristic of the metal, the current stops increasing. The lower threshold, when the cathode is initially negatively charged, Lenard explained as an effect of what we

⁴⁷H. A. Lorentz, "Optische verschijnselen die met de lading en de massa der ionen in verband staan, I," *Versl. Kon. Akad. Wetensch. Amsterdam*, 6 (1898), 506-519, on 514. An English translation appears in Lorentz, *Collected Papers*, 3 (Hague, 1936), 17-29.

⁴⁸Thomson's 1899 talk to the British Association was "On the Existence of Masses Smaller than Atoms." He published a complete discussion in "On the Masses of the Ions at Low Pressures," *Phil. Mag.*, 48 (1899), 547-567.

⁴⁹J. Thomson, *Notes on Recent Researches in Electricity and Magnetism* (Oxford, 1893), pp. 64-68.

⁵⁰Righi had shown that a neutral plate will attain a characteristic maximum positive potential when illuminated; "Di alcuni nuovi fenomeni elettrici provocati dalle radiazioni," *Rendiconti R. Accad. Lincei*, 4 (1888), 185-187.

now call a "space-charge." The accumulation of negatively charged, low velocity electrons just off the surface of the cathode forms an electrostatic barrier for the escape of others.⁵¹ But the existence of a current which overcomes a decelerating external field indicates that some electrons are released from the cathode with relatively high initial velocities. Lenard thought this behavior "not immediately understandable" and undertook a detailed study of the charge transported as a function of potential.

In March 1902 he published his findings.⁵² He first sought the relation of light intensity to current by measuring the charge transferred in equal time intervals from the aluminum plate U to the reference electrode E in the tube pictured in Figure 1. By moving the spark source of ultraviolet light, L , he showed that the photocurrent is strictly proportional to the light intensity.⁵³ He was struck by the immense range over which this relation held: he could not find light of so low an intensity that no current passed. Trials with light reflected off a lampblackened surface showed that the proportionality of current to light intensity was valid even when the intensity changed by a factor of three million.

This forced Lenard to study separately the effect on all his measurements of the component of photocurrent due to the light reflected off U and back to E . This weak light will stimulate photoemission from E . By assuming that this reversed photocurrent is similar in form to the primary, only proportionally weaker, he could correct for the reflection. If $U(x)$ is the total current as a function of potential, the corrected function $Y(x)$ is $U(x) - R(x)$, where $R(x)$ is the reflection component. Because both electrodes are made of the same material, $R(x)$ must have the same form as $Y(x)$ except that x is reversed. If $Y(x)$ is normalized to 1, one has simply $R(x) = -A \cdot Y(-x)$, where A is the proportionality constant.

To establish the proportionality, Lenard determined the ratio of the saturation current in the reversed and forward directions, respectively. He found that this ratio was independent of the light intensity. This was not surprising; the ratio is essentially a measure of the relative reflectivity of the electrode material. But Lenard noted that "the type of light was of noticeable influence" on the ratio. The ratio also varied with the material out of which the cathode was made. With

⁵¹Lenard, *op. cit.* (note 41), p. 1665.

⁵²Lenard, *op. cit.* (note 2).

⁵³Stoletov had concluded in 1889, on the basis of a single measurement, that the photocurrent is proportional to the light intensity; "Sur les phénomènes actinométriques," *Comptes rendus*, 108 (1889), 1241-1243.

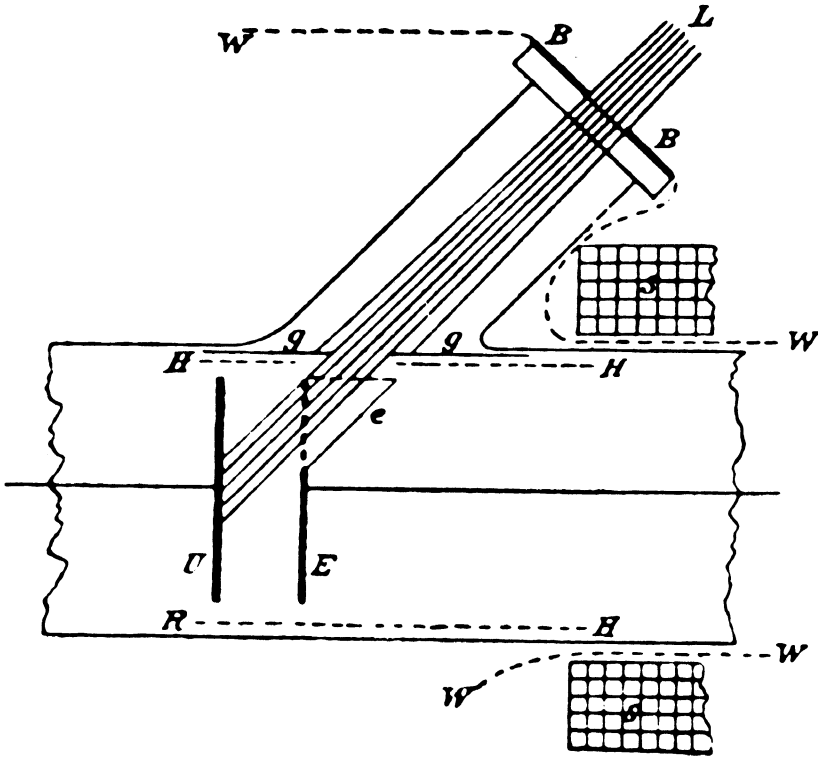


Figure 1.

these puzzles in mind, Lenard then turned to the chief issue of his study: the variation of photocurrent with accelerating potential.

4. SUCCESS: EXPERIMENTS IN 1902

In 1899 Lenard had thought that the critical decelerating potential at which the current reached saturation was determined in part by the intensity of the light.⁵⁴ He now wondered if the velocities of the cathode rays might not be determined entirely by the properties of the cathode. He had already shown that the cathode rays come exclusively from the cathode material. The critical potential is that decelerating voltage that just suffices to stop those electrons that have the greatest velocity. Might it, like the relative reversed saturation

⁵⁴Lenard, *op. cit.* (note 41), p. 1665.

current A , be entirely independent of the light intensity and depend only on the type of light?

To examine the relationship of current to potential, Lenard measured two currents separately: 1) the negative charge leaving the photocathode U and 2) that arriving at the reference electrode E . Figure 2 is his graph of the result. The horizontal axis represents the difference in potential between U and E , with positive values indicating that the potential at E is greater than at U . The vertical axis measures the charge per unit time normalized to the saturation current. The heavy solid line traces the type 1 current, the dashed line represents type 2. The other lines indicate measurements of the first kind for different plate separations and need not concern us here.

Lenard's results are most easily understood if we discuss them separately for the five sections which Lenard indicated by Roman numerals beneath the horizontal axis. In *region I* the positive potential at the photocathode U is great enough to pull all electrons released by the light back to U . The net charge leaving U and that arriving at E would be zero if light were not reflected off U to E . This low intensity light releases electrons from E which accelerate to U . Therefore the graph shows a negative reading for both type 1 and type 2 currents.⁵⁵ In *region II* the retarding potential is lower and allows some electrons to escape from U to the walls of the tube but not to E . *Region III* begins when more electrons reach E than are lost due to the reflected light. Here the dashed curve first assumes a positive value. In *region IV* the potential is favorable for the passage of electrons to E . But the electrons must still overcome the space charge concentration. The net current which actually leaves U is equal to that which arrives at E ; but if the potential difference is increased, greater numbers of electrons will penetrate the space charge. *Region V* begins at the saturation potential. For this and all greater potential differences *all* electrons released by the light from U flow to E .

The key result of the study emerged when Lenard realized that he had found a means to measure the maximum velocity of photoelectrically released electrons. The null point in the solid curve which marks the beginning of *region III* occurs at a retarding potential weak enough so that the number of very fast electrons which escape from U equals the very small number released from E by reflected light. Since this is only a minute fraction of the total number of electrons released

⁵⁵Note that the solid line in Figure 2 represents negative charge leaving U per unit time; a negative value denotes a flow of negative charge to U . The dashed line represents negative charge arriving at E ; a negative value of the dashed curve denotes negative charge leaving E .

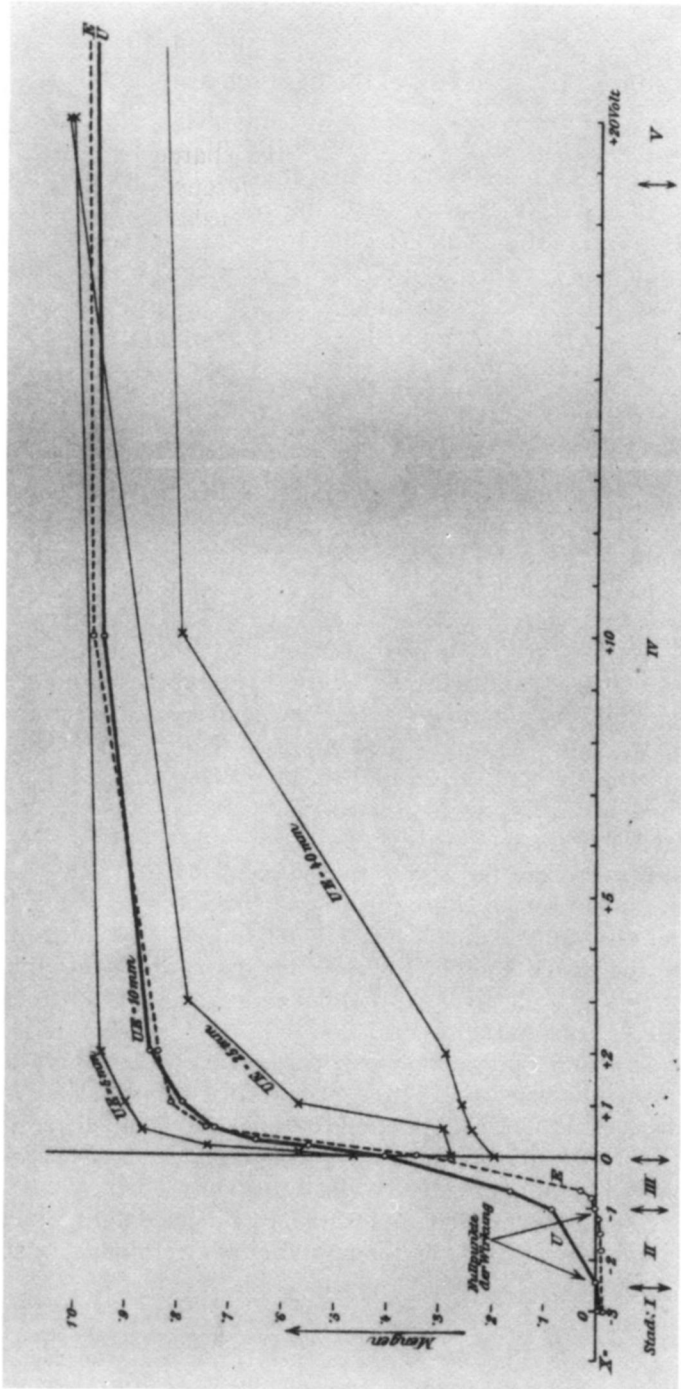


Figure 2.

from U by the light, the potential of the null point is a sensitive indicator of the maximum initial electron velocity. Even more useful as a measure of maximum electron velocity is the null point on the dashed line for charge arriving at E . There are only a few electrons—those comprising the high end of the velocity distribution and equal in number to those released from E by reflected light—that are able to overcome the retarding potential between U and E . Lenard discovered that the null potential *did not vary* appreciably when the intensity of the light was changed, either by moving the arc lamp or by passing more current through it.⁵⁶ Therefore, he concluded, electron velocity is independent of the light intensity.

Lenard knew that an electron is only released from an atom if its accumulated kinetic energy exceeds the intra-atomic binding energy. One would expect that the incident light sets electrons into resonant oscillation. But if this is the case the electron can acquire the extra energy, expressed as motion outside the atom, only during the final half oscillation before its ejection. In that event, the energy should increase with light intensity. The greater the amplitude of the transverse electric field vibration, the greater the energy transferred to the electron. But Lenard found, on the contrary, that there was no dependence of electron velocity on the light intensity. He concluded that light energy is not transformed into electron energy in the photoeffect. The light only stimulates atoms by resonance to release electrons; it contributes no energy. Once free, electrons fly off with a velocity determined by their previous motion within the atom. "The light plays only the role of triggering [the release of] a motion which already exists with full velocity inside the atoms."⁵⁷

There was still a problem to explain. Lenard observed that the maximum electron velocity depended on the type of light he used. He suggested that light affects a cathode in a manner which is characteristic of its spectral composition. An electron can be released only when the frequency of the light matches the frequency of oscillation of the electron in the atom. Different light sources can therefore trigger electrons with different velocities from the same cathode. But there is a maximum velocity for any given cathode material. An electron with this velocity can only be released if the light contains a specific frequency, namely that characteristic of the mechanical vibration of the fastest electron in the atom. In other words, the distribu-

⁵⁶Lenard, *op. cit.* (note 2), p. 168. For an anticipation of this key result see Henri Buisson, "Mesure de la vitesse des particules électrisées dans la décharge par la lumière ultra-violette," *Comptes rendus*, 127 (1898), 224–226.

⁵⁷Lenard, *op. cit.* (note 2), p. 150.

tion of possible electron velocities is determined exclusively by the structure of the atom; the light picks out a subset of that distribution.

The photoelectric effect, viewed in this way, became a valuable tool to probe the atom. The velocity distribution of photoelectrons reflects the dynamic activity within the undisturbed atom. The velocity of the fastest electron is a function of the cathode material and of the type of light, not of light intensity. Only the total number of emitted electrons is proportional to the intensity. Lenard had corroborated his long held conviction that the photoelectric effect depends solely on properties of the cathode.

Lenard made no attempt in this study or in subsequent studies to correlate light frequency with electron velocity.⁵⁸ Having found a means to probe the uncharted interior of the atom, he turned away from study of the light. The light was incidental to him; the velocity distribution of electrons within atoms was the fundamental goal. The observed velocity distribution triggered by light of one kind was only a part of the internal distribution. The combined results of trials with many types of light would reveal the atomic order.

5. THE TRIGGERING HYPOTHESIS, 1902–1911

In the early years of this century, Lenard developed a qualitative model of atomic structure based on his studies of the production and absorption of photoelectrons. In 1902 he measured the mean free path of cathode rays just energetic enough to induce conductivity in a gas and concluded that each gas atom has, "within its impenetrable volume, a structure of fine elements containing many interstices, [and] hence is capable of many possible motions."⁵⁹ He suggested that the interior of the atom might be largely empty space. The motion of electrons defined the dimension of the dynamic atom. In 1903 he spoke of atoms built out of indistinguishable units that he called "dynamids." The number of dynamids in an atom is proportional to the weight of the atom. Each electrically neutral dynamid contains electrons together with an equivalent positive charge in a stable dynamic configuration; the simplest case is a dipole.⁶⁰

⁵⁸Within a year Lenard investigated metal arc spectra in the ultraviolet region and gave no thought to the photoeffect; "Über den elektrischen Bogen und die Spektren der Metalle," *Ann. Physik*, 11 (1903), 636–650.

⁵⁹Lenard, *op. cit.* (note 2), p. 192.

⁶⁰P. Lenard, "Über die Absorption von Kathodenstrahlen verschiedener Geschwindigkeit," *Ann. Physik*, 12 (1903), 714–744, on 735–736.

Lenard also studied the emission of light. He described the secondary emission of cathode rays—which occurs when a primary cathode-ray beam strikes a metal electrode—as “completely analogous” to the photoelectric effect.⁶¹ He thought that an electron in an atom could be released from its dynamid by the ether oscillations of light or by the as yet unexplained ether “process” which constituted the electron. Work on fluorescence in rare-earth alkalis led him in 1908 to propose that photoelectric and cathode-ray stimulation affects only certain groups of molecules which he called “centers.” Fluorescence occurs when electrons return to equilibrium in these atomic centers. “The excitation of a phosphor,” he said, “consists in the polarization of the centers, i.e., in the permanent ejection of quanta (electrons) from the metal atoms in the center; . . . light emission from the phosphor occurs when electrons return.”⁶²

Lenard’s largely empty atom, which emits characteristic spectral lines when free electrons return to equilibrium in the dynamic atomic structure, is suggestive of the atom proposed five years later by Niels Bohr. But there are fundamental differences. Lenard’s was never a quantitative atom theory. It was primarily because of his remarkable experimental skill that his ideas about atoms drew support in Germany. His triggering hypothesis for the photoelectric effect required that each electron within the atom has a velocity which is related in a consistent way to its mechanical frequency. The specific relation of frequency to velocity for each cathode material could only be determined by experiment. The photoelectric effect did not predict what the relationship would be, it only made it accessible to observation. The triggering hypothesis formed the bridge which connected the photoelectric effect to the issues of atomic structure.

In 1909 Lenard’s triggering hypothesis was included by a knowledgeable reviewer among “the generally accepted truths of physics.”⁶³ Albert Einstein, who characterized Lenard’s experimental work on the photoeffect as “pathfinding,” proposed an alternative interpretation in 1905.⁶⁴ But Einstein’s light quantum, which explained Lenard’s results at the cost of rejecting classical wave radia-

⁶¹P. Lenard und V. Klatt, “Über die Erdalkaliphosphore,” *Ann. Physik*, 15 (1904), 633–672, on 672.

⁶²P. Lenard und S. Saeland, “Über die lichtelektrische und aktinodielektrische Wirkung bei den Erdalkaliphosphoren,” *Ann. Physik*, 28 (1909), 476–502, on 501–502.

⁶³R. Ladenburg, “Die neueren Forschungen über die durch Licht- und Röntgenstrahlen hervorgerufene Emission negativer Elektronen,” *Jahrb. Radioak. Elek.*, 6 (1909), 425–484, on 427.

⁶⁴A. Einstein, “Über einen Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt,” *Ann. Physik*, 17 (1905), 132–148, on 145.

tion, had little support early in the century.⁶⁵ Lenard told Einstein that he would only be satisfied when the “comprehensive and marvellous relationships” which Einstein had proposed succeeded in bringing the unity that Lenard expected to find among the problems which remained.⁶⁶ Most physicists felt that experiment would confirm the triggering hypothesis. Investigation of the relation between light frequency and electron velocity began in 1907, largely in an attempt to “give further support” to Lenard’s explanation.⁶⁷

There were some problems. If the electron takes its velocity from within the atom, heating the cathode should increase the speed of the emitted electrons. Tests failed to find the increase.⁶⁸ Furthermore, the experimental data was unclear about whether the interaction was truly a resonance. Some thought that peaks had been found in photo response at specific frequencies.⁶⁹ Others emphasized the continuity of the response to frequency.⁷⁰ The issue was important because the triggering mechanism demanded an inordinately large number of electron motions in the atom if the response were continuous. Einstein had predicted that a continuous linear relation between frequency and stopping potential would be found. But the empirical data was in doubt until 1915. With an appropriate atom model, like those proposed by Thomson in 1910 and 1913, even the Einstein law could be reconciled with the triggering mechanism.⁷¹

⁶⁵The reasons for the opposition to Einstein’s hypothesis are discussed in Wheaton, *op. cit.* (note 38). An example is given by Christoph Ries, *Das Licht in seinen elektrischen und magnetischen Wirkungen* (Leipzig, 1909), pp. 114–135. Ries devoted a twenty page section to theories of the normal photoeffect but did not mention Einstein’s hypothesis.

⁶⁶Lenard to Einstein, 5 May 1909. Einstein Archive, Princeton, New Jersey. Einstein’s attitude toward Lenard may be reconstructed from his letters to Jakob Laub who was Lenard’s assistant in 1910–1911. Copies of these letters are held at the Einstein Archive.

⁶⁷E. Ladenburg, “Über Anfangsgeschwindigkeit und Menge der photoelektrischen Elektronen in ihrem Zusammenhange mit der Wellenlänge des auslösenden Lichtes,” *Verh. Deut. phys. Gesell.*, 9 (1907), 504–514.

⁶⁸E. Ladenburg, “Über den photoelektrischen Effekt bei hohen Temperaturen,” *Verh. Deut. phys. Gesell.*, 9 (1907), 165–174; R. A. Millikan and George Winchester, “The Influence of Temperature upon Photoelectric Effects in a Very High Vacuum and the Order of Photoelectric Sensitivities of the Metals,” *Phil. Mag.*, 14 (1907), 188–210.

⁶⁹Ladenburg, *op. cit.* (note 67); A. Sommerfeld, “Application de la théorie de l’élément d’action aux phénomènes moléculaires non périodiques,” *La théorie du rayonnement et les quanta*, P. Langevin and M. de Broglie, eds. (Paris, 1912), pp. 313–372, on 355.

⁷⁰A. Joffé, “Eine Bemerkung zu der Arbeit von E. Ladenburg,” *Ann. Physik*, 24 (1907), 939–940; R. Pohl and P. Pringsheim, “Über die langwellige Grenze des normalen Photoeffektes,” *Verh. Deut. phys. Gesell.*, 15 (1913), 637–644.

⁷¹J. Thomson, “On the Theory of Radiation,” *Phil. Mag.*, 20 (1910), 238–247; “On the Structure of the Atom,” *Phil. Mag.*, 26 (1913), 792–799, and addendum, *ibid.*, p. 1044.

The triggering hypothesis failed for other reasons. Wilhelm Wien, Johannes Stark, and J. J. Thomson all expressed reservation in 1907 that triggering could explain ionization by X rays.⁷² The triggering hypothesis for visible and ultraviolet light continued to be accepted until 1911. Lenard himself provided the data that did the most damage. His studies of ionization in gases by ultraviolet light failed to produce any cases of strong ionization unaccompanied by absorption of the light. This forced him to admit that some of the electron energy comes from the light.⁷³

Once the photoelectric effect was an acknowledged transformation of energy, the advantage of the triggering hypothesis was lost. Triggering had enabled one to avoid having to explain how energy is absorbed from waves. Paradoxes had arisen in attempts to understand ionization on the basis of classical spreading waves, but these problems had been largely restricted to ionization by X rays and γ rays. After 1911 the triggering hypothesis for ionization by ordinary light had to confront the same problems. The techniques that had been developed to treat the paradoxes for X rays and γ rays could not be applied to periodic light waves.⁷⁴ The triggering hypothesis had outlived its usefulness. Lenard suggested a qualitative reconciliation of the light quantum with wave radiation in 1910, but a year later he felt that "a complete theory of the energy transformation in the photoelectric effect is not yet possible."⁷⁵ In 1913 he admitted that the photoeffect was a "difficulty," one which became insurmountable after the acceptance of the Bohr theory of the atom.⁷⁶ With the success of the Bohr theory, Lenard's atomic hypotheses fell into neglect.

The triggering hypothesis was discarded before Millikan verified Einstein's law in 1915.⁷⁷ Millikan's experiments did not disprove the triggering hypothesis, nor did they bring about the acceptance of the

⁷²Wheaton, *op. cit.* (note 38), chapters 5 and 6.

⁷³P. Lenard and C. Ramsauer, "Über die Wirkung sehr kurzwelligen ultravioletten Lichtes auf Gase und über eine sehr reiche Quelle dieses Lichtes. V. Teil. Wirkung des stark absorbierbaren Ultraviolett und Zusammenfassung," *Sitzbr. Heidelberg Akad. Wiss., math. naturwiss. Kl., 2a* (1911), section 24, 5-8, 47; see also Ramsauer, "Über die Wirkung sehr kurzwelligen ultravioletten Lichtes auf Gase," *Phys. Zs.*, 12 (1911), 997-998.

⁷⁴A. Sommerfeld, "Über die Struktur der γ Strahlen," *Sitzbr. math. phys. Kl. Akad. Wiss., München* (1911), pp. 1-60.

⁷⁵P. Lenard, "Über Äther und Materie," *Sitzbr. Heidelberg Akad. Wiss., math. naturwiss. Kl., 1* (1910), section 16, 17-18; Lenard and Ramsauer, *op. cit.* (note 73), p. 7.

⁷⁶P. Lenard, "Über Elektrizitätsleitung durch freie Elektronen und Träger, II," *Ann. Physik*, 41 (1913), 53-98, on 82.

⁷⁷R. A. Millikan, "A Direct Determination of 'h'," *Phys. Rev.*, 4 (1914), 73-75; "A Direct Photoelectric Determination of Planck's 'h'," *Phys. Rev.*, 7 (1916), 355-388.

light quantum. In the decade from 1913 to 1923 the paradoxes confronting radiation theory were largely ignored.⁷⁸ In this period there simply was no convincing theoretical explanation of the photoelectric effect.⁷⁹ At its end the light quantum was reluctantly adopted to relieve what had become an intolerable state of affairs.

Once again Lenard's work was eclipsed. In 1920, just before the light quantum was incorporated into physics, Lenard reiterated the hopes he had placed in the photoelectric effect. But without the triggering hypothesis, he could no longer assert that photoelectrons reveal energies characteristic of the atom, and his claim was only a shadow of what it had once been. The slow electrons released by the photoelectric effect, he said, "promised to give the best information on the forces of atoms, the constitution of matter."⁸⁰

⁷⁸Wheaton, *op. cit.* (note 38), chapters 7 and 9.

⁷⁹R. Stuewer, "Non-Einsteinian Interpretations of the Photoelectric Effect," *Minnesota Studies in the Philosophy of Science*, R. Stuewer, ed. (Minneapolis, 1970), 5, 246-263.

⁸⁰Lenard, *op. cit.* (note 13), p. 38.