17

Albert Einstein

1879-1955

The Photoelectric Effect

EARLY in the twentieth century the scientific world had the good fortune to witness the achievements of one of its most remarkable minds. Only when viewed in full historical perspective will the contributions of Albert Einstein assume their total significance in the evolution of scientific thought. Nonetheless, for the great reach of his imagination and the power of his conceptual schemes, he had no equal among contemporary scientists. His scientific stature was enormous, both in the eyes of his colleagues and of the public at large. Rarely in the history of physics has a scientist been accorded so much public acclaim. Not since Newton, in fact, was there a physicist who attracted as much universal attention. Indeed, the two are frequently compared on the basis of the great influence each had on the development of physics. In their methods, however, they differed in one major respect: Newton was primarily an experimenter, although his law of gravitation was largely the result of theoretical speculation. Einstein, on the other hand, was a theorist who did no experimental work whatever in the course of his investigations. They shared the distinction of unifying great blocks of knowledge having universal application.

Einstein is perhaps best known for his theories of relativity,* yet he worked in many fields, particularly in the kinetic theory of matter and the quantum theory of light. It was in connection with the latter, for his explanation of the photoelectric effect,[1] that he won the Nobel prize in 1921. The photoelectric effect was discovered experimentally by Hertz in 1887, in

* See Appendix, page 313.

[1] Photoelectricity generally includes three distinct phenomena, the *photovoltaic, photoconductive*, and *photoemissive* effects. The last, with which we are concerned here, is usually called the photoelectric effect.

the course of his researches on electric waves. He noticed that the sparks produced in the gap of his secondary or *detector* circuit were influenced by the light falling upon the gap from the sparks in the primary or *transmitting* circuit. Upon further investigation, Hertz concluded that it was the ultraviolet portion of the light that was responsible for the phenomenon, and that the effect was greatest when the light was incident upon the negative terminal (cathode) of the gap. Being concerned mainly with other problems, Hertz did not carry these studies very far, leaving to others the more detailed investigations. Many were attracted to the problem, but the most significant contributions were made by Wilhelm Hallwachs (1859–1922), who showed that the emission consisted of negative electricity, and by Lenard, who measured the $\frac{e}{m}$ of the photoelectric carriers and found it to be the same as that determined by Thomson for cathode rays.

By the early part of the twentieth century two empirical laws had been firmly established. First, the photoelectric current, or number of electrons emitted per unit time, was proportional to the intensity of the incident light. Second, the maximum energy of the emitted electrons was proportional to the frequency of the light, not to its intensity. It was at this point, in 1905, that Einstein showed how Planck's new quantum theory of radiation could be used to account for the photoelectric effect. His solution was notable for its simplicity, yet it accounted fully for the observed facts. In that same year he made his first discoveries in the field of relativity.

Albert Einstein was born on March 14, 1879, at Ulm, Württemberg, in South Germany, where his father was a small businessman. Germany was then in a period of rapid economic growth following the Franco-Prussian War and the formation of the empire several years earlier. Bismarck had forged an empire that could not be contained in its own territory; its enormous industrial expansion, with the consequent need for new markets, coupled with notions of racial and cultural superiority, led to two world wars. Einstein was involved in both; in the first, although a Swiss neutral, he supported the pacifist movement. In the second, while he found the thought of war no less deplorable, he could no longer justify his own total pacifism and therefore became instrumental in persuading the United States government to attempt the development of atomic weapons.

His early years were spent in Munich, where his family had settled shortly after he was born. There he attended elementary school and the gymnasium,[2] showing no particular aptitude nor interest in his studies. He enjoyed learning by himself, however, and devoted much of his time to reading in mathematics and science. When he was fifteen, his family moved to

[2] Roughly the equivalent of high school plus junior college.

Milan to seek better economic conditions and young Einstein left the gymnasium without taking the examinations required for admission to a university. The following year he attended the Cantonal School at Aarau, Switzerland, where he won his certificate, and then entered the Zurich Polytechnic. There, strangely enough, his chief interest was in experimental physics. He spent a great deal of time in the laboratories, but continued to read all that he could of the current ideas in physics, studying on his own, for the most part.

Einstein graduated from Zurich in 1900, then did some private tutoring while he acquired Swiss citizenship, and in 1902 was appointed an examiner in the Swiss Patent Office. By his own account his years there were very pleasant; there he found the time to develop his major ideas. During the next two years he published five papers, chiefly on kinetic theory and thermodynamics. These showed marked ability, but in 1905 he achieved true greatness with his papers on the quantum theory of light and on special relativity. That same year he completed a dissertation* for his doctorate. By then he was reasonably well known; he began to lecture at Bern University, meanwhile retaining his position in the Patent Office. In 1909 he became assistant professor at the Zurich Polytechnic, and two years later accepted an appointment as full professor at the German University in Prague. He returned to Zurich shortly afterward as a full professor, remaining there until 1914, when he was invited to the Kaiser Wilhelm Institute in Berlin, then one of the leading research centers in the world. While there he published his theory of general relativity in 1916, the predictions of which were confirmed by astronomical observations three years later.

As the Nazi mentality began to creep over Germany it became clear that Einstein could no longer remain. German culture was being sacrificed to distorted ambitions, and even scientific truths were suspected of racial taint. Einstein, being a Jew, realized that his own future, both as a scientist and as an individual, was no longer secure in Hitler's Germany and reluctantly decided to leave. In 1933 Einstein joined the Institute for Advanced Studies at Princeton, where he remained for the rest of his life. His presence there enriched the Institute, as well as the entire scientific world. He continued to work quietly, seeking to complete his unified field theory, lending his support to various movements in search of world peace, and condemning ignorance and bigotry wherever he found it. He died on April 18, 1955, shortly before the fiftieth anniversary of his most important discovery, the theory of relativity.

The following extract, taken from the *Annalen der Physik*, vol. 17 (1905), page 144, contains his explanation of the photoelectric effect.

* On a new method of determining the size of molecules.

Einstein's "Experiment"

The common conception that the energy of the light is distributed evenly over the space through which it is propagated, encounters especially great difficulties in the attempt to explain the photoelectric effects which have already been shown in the pioneering work due to Mr. Lenard.*

According to the theory, that the incident light is composed of quanta of energy $\left(\frac{R}{N}\right)\beta\nu$, the origin of the cathode rays may be interpreted in the following manner.■ The quanta of energy penetrate the surface of the material and their respective energies are at least in part changed into the kinetic energy of electrons. The simplest process conceivable is that a quantum of light gives up all its energy to a single electron. We shall assume that this happens, but at the same time not exclude the possibility that the electron absorbs only a fraction of the incident energy. Upon reaching the surface, an electron originally inside the body will have lost a part of its kinetic energy. Furthermore one may assume that each electron in leaving the body does an amount of work P, which is characteristic of the material. Those electrons that are ejected normal to and from the immediate surface will have the greatest velocities.■ The kinetic energy of these electrons is

$$\frac{R}{N}\beta\nu - P$$

If the body is charged to the positive potential π and surrounded by conductors at zero potential, and if this voltage is just sufficient to prevent the loss of charge from the surface then it must be that

$$\pi\epsilon = \frac{R}{N}\beta\nu - P$$

where ϵ is the electronic charge, or

$$\pi E = R\beta\nu - P'$$

where E is the charge of a gram equivalent of the univalent ion and P' the potential of this amount of negative charge with respect to the body.■

If E is set equal to 9.6×10^3 then $\pi \times 10^{-8}$ is the potential in volts which the body will assume when irradiated in a vacuum.

$\frac{R}{N} = k$, the Boltzman constant, where R is the Molar gas constant and N the Avogadro number. Thus, $\beta = \frac{h}{k}$, where h is Planck's constant, and the quantum of energy is then $h\nu$.

The electron must overcome the attractive forces holding it to the material. P is known as the photoelectric work function of the material.

Usually written as $\frac{1}{2}mv^2 = h\nu - W = \epsilon V$ where V is the retarding potential required to stop, the fastest photoelectrons.

E is the Faraday, equal to 9650 emu per gram-equivalent, or 96,500 coulombs per gram equivalent.

* P. Lenard, *Ann. d. Phys.* 8 (1902), pp. 169-170.

To see whether the relation derived agrees with observations in order of magnitude we take $P' = O$, $\nu = 1.03 \times 10^{15}$ (which corresponds to the limit of the sun's spectrum in the direction of the ultraviolet), and $\beta = 4.866 \times 10^{-11}$. We thus obtain $\pi \times 10^{-8} = 4.3$ volts, which in order of magnitude agrees quite well with the results of Mr. Lenard.*■

$R = 8.31 \times 10^7$ erg/mole K°.

If the formula derived is correct, it would follow that π, if plotted in cartesian coordinates as a function of the frequency of the exciting photons, would yield a straight line whose slope is independent of the material under investigation.■

From which Planck's constant is determined. The experimental verification of Einstein's photoelectric equation, and the determination of the Planck constant, were accomplished by R. A. Millikan in 1916.

As far as I can see our ideas are not contrary to Mr. Lenard's observations on the photoelectric effect. If each quantum of light were to give its energy to the electrons independently of all the others then the velocity distribution, i.e., the quality of the cathode rays produced, will be independent of the intensity of the exciting radiation; on the other hand the numbers of electrons leaving the body under equal conditions will be directly proportional to the intensity of the incident radiation.†

In the preceding it has been assumed that the energy of at least some of the quanta of the incident light had been given completely to individual electrons. If this plausible assumption had not been made, then one would have obtained, instead of the above equation, the following inequality

$$\pi E + P' \leqq R\beta\nu$$

For the case of cathode luminescence,■ which is the inverse of the process just considered, one obtains by similar reasoning:

The emission of light from a surface when bombarded by electrons.

$$\pi E + P' \geqq R\beta\nu$$

For the materials investigated by Mr. Lenard, πE is always considerably greater than $R\beta\nu$, since the voltage through which the electrons must have fallen in order to produce visible light is in some cases hundreds and in others, thousands of volt.** It must therefore be assumed that the kinetic energy of an electron is employed in the production of a great number of quanta of light.

We shall have to assume, that in the ionization of a gas by means of ultraviolet light each absorbed quantum of light energy is used up in the ionization of a single gas molecule. It follows therefrom that the work necessary theoretically for ionization of the molecule cannot be greater than the energy of the absorbed effective quantum of light energy. If J represents the theoretical ionization energy per gram equivalent then

* *Ibid.*, p. 165 and p. 184.
† *Ibid.*, p. 150 and pp. 166–168.
** P. Lenard, *Ann. d. Phys. 12* (1903), p. 469.

$$R\beta\nu = J$$

According to Lenard's measurements the greatest effective wavelength for air■ is about 1.9×10^{-5} cm and therefore

That is, the longest wavelength of light that can ionize the air.

$$R\beta\nu = 6.4 \cdot 10^{12} \text{ erg} \geqq J$$

An upper limit for the ionization potential may be obtained from the ionization voltages in rarefied gases. According to J. Stark* the smallest measured ionization voltage in air is approximately 10 volts (for Pt anodes)■ and therefore the upper limit for J is 9.6×10^{12}, which is rather close to the value just found. There is one other consequence whose experimental verification seems to me of great importance. If each absorbed quantum ionizes a molecule, then there has to exist a relation between the absorbed amount of light L and the number j of gram molecular weights, thereby ionized, namely

The nature of the electrodes, in principle, should not affect the ionization potential of the gas.

$$j = \frac{L}{R\beta\nu}$$

This relation must, if our concept corresponds to reality, be valid for every gas which (at the frequency considered) does not show absorption without corresponding ionization.■

At potentials below the ionization potential the gas could absorb by excitation.

* J. Stark, *Die Elektrizität in Gasen* (Leipzig, 1902), p. 57.

SUPPLEMENTARY READING

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