## Cover Story (Cont. from Vol. 15 No. 1)

# Einstein's Photon Hypothesis and Its Impact on Science and Technology

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*In celebration of the World Year of Physics 2005, Einstein's photon hypothesis proposed exactly a hundred years ago is reviewed along with its enormous impact on science and technology still lasting over a century. In the first half of the article, the photon hypothesis and the law of photoelectric effect and their impact on the progress of modern physics are discussed. The latter half reviews the application of these theories mainly to photodetection devices with emphasis on the historical evolution of the new technologies.*

Keywords: Einstein, Photon hypothesis, photoelectric effect, photodetector, photomultiplier tube, photodiode, solar cell, CCD image sensor.

### 1. INTRODUCTION

In 1922 Albert Einstein was awarded the Nobel Prize in physics 1921 for his services to theoretical physics, and especially for his discovery of the law of the photoelectric effect. The photoelectric effect refers to change of electrical conduction properties in matter induced by light and other forms of electromagnetic radiation. In order to induce this effect, the absorption of incident light by matter should cause a generation of charged carriers, such as conduction electrons and positive holes in the case of a semiconductor, or free electrons (photoelectrons) emitted from a metal surface with immobile positive ions left behind. These two phenomena are called the internal photoelectric effect and external photoelectric effect, respectively.

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Around the turn of the 19th-20th century, the study of the external photoelectric effect was of major importance in the development of physics. Several experimental results had been accumulated, but some of them could not be accounted for on the basis of electromagnetic wave theory of James C. Maxwell.

Einstein completed a paper on March 17, 1905, in Bern, Switzerland, just 3 days after his 26th birthday, and submitted to "Annalen der Physik" (Annuals of Physics) [1]. In this paper entitled "Ueber einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt" (On a heuristic point of view concerning the generation and transformation of light), Einstein proposed the concept of "Lichtquant" (light quantum) and beautifully explained the law of the photoelectric effect.

Of course, the idea of a granular structure of radiation implied the particle nature of light and inherently challenged the prevailing well-established electromagnetic theory of light. Consequently, it took more than ten years before his theory finally came to be admitted and honored by a majority of physics community. However, we have evidenced that Einstein's photon hypothesis or corpuscular theory of light, along with de Broglie's material wave theory of particles, eventually urged the progress of quantum mechanics.

From the viewpoint of application of physics to human life, Einstein's photoelectric theory seems to be far more important than any other physics theory discovered by him. Today, it still gives us the basis for photo-detection devices such as photomultipliers, photodiodes, and CCD image sensors, as well as photovoltaic energy converters. In the latter half of this article, some aspects of the practical impact of Einstein's photon hypothesis on science and technology will be reviewed.

## 2. PHOTON HYPOTHESIS AND EXPLANATION OF PHOTOELECTRIC EFFECT

First of all, let us study the original paper by Einstein published in 1905 [1]. The English translation is also available in Ref. [2].

At the end of introductory part on the second page of his paper, Einstein wrote: "Indeed, it seems to me that the observation regarding black-body radiation, photoluminescence, production of cathode rays by ultraviolet light, and other groups of phenomena associated with the generation or conversion of light can be understood better if one assumes that the energy of light is discontinuously distributed in space. According to the assumption to be contemplated here, when a light ray is spreading from a point, the energy is not distributed continuously over ever-increasing spaces, but consists of a finite number of energy quanta that are localized in points in space, move without dividing, and can be absorbed or generated only as a whole."

Then in Section 1~6, he discussed the black-body radiation in detail and showed that "Monochromatic radiation behaves thermodynamically as if it consisted of mutually independent energy quanta of magnitude $R\beta\nu/N$." Here, $\nu$ is the frequency of the radiation, $R/N$ is the gas constant over Avogadro's number which is equal to $k$ (Boltzmann's constant), and $\beta$ is Wien's exponential coefficient that corresponds to $h/k$. Therefore, the magnitude of energy quantum is $h\nu$ and proportional to $\nu$ multiplied with Planck's constant $h$.

This hypothesis was immediately applied to three other problems in the following sections. In Sec. 7, Einstein made a very clear interpretation of Stokes' law in photoluminescence. The term Lichtquant (light quantum) was used here for the first time. The interpretation can be summarized as follows: if a light quantum of frequency $\nu_1$ is absorbed and gives rise to the generation of a light quantum of frequency $\nu_2$, the energy of the latter energy quantum cannot be greater than that of the former, and hence,

$$h\nu_2 \leq h\nu_1, \text{ or } \nu_2 \leq \nu_1. \tag{1}$$

(Hereafter, notation $h$ is used instead of $R\beta/N$ for the sake of simplicity.)

In Sec. 8 "On the generation of cathode rays by illumination of solid bodies," he proposed what later became known as Einstein's photoelectric equation, and gave a clear explanation for the external photoelectric effect. Emission of photoelectrons from the surface of a metal due to ultraviolet or visible radiation had been studied since late 1880s, and Philipp Lenard made the most extensive study [3]. The key points of experimental results were summarized as follows: (i) the number of photoelectrons emitted is proportional to the intensity of the incident radiation, (ii) there exists a minimum frequency of radiation for the photoelectron emission, and the minimum frequency differs from one metal to the other, (iii) the kinetic energy of a photoelectron does not depend on the intensity of incident radiation, but the energy increases as the frequency of incident radiation increases. It was then very difficult to understand from the electromagnetic wave theory of light the experimental results (ii) and (iii) above.

Einstein overcame this difficulty by introducing the famous photoelectric equation with his name,

$$E_{max} = h\nu - W, \tag{2}$$

where $E_{max}$ is the maximum kinetic energy of photoelectrons, $h\nu$ is the energy of light quantum of incident radiation, and $W$ is the work done by each photoelectron in leaving the metal surface (later called as "the work function"). Here it was assumed that a single light quantum is absorbed in the metal and the total or part of the energy of light quantum is transferred to a single electron to be emitted.

Today, we can clearly understand from the above equation why the experimental observations (ii) and (iii) mentioned above hold true. A hundred years ago, however, it took over 10 years before Einstein's photon hypothesis was understood and accepted. By the way, the Nobel Prize in physics in 1905 was awarded to Lenard for his work on cathode rays.

## 3. EVOLUTION OF THE PHOTON HYPOTHESIS

In the early 20th century, it was not so easy to verify the validity of Einstein's photoelectric equation (2) by precise measurements. In 1916, Robert Millikan, after his endeavor over 10 years, finally provided an incontrovertible proof of the direct proportionality between the kinetic energy of photoelectrons and the frequency of absorbed light [4]. He showed that the proportionality constant $h$ is independent of the material and nature of the surface, and that its value is about $6.57 \times 10^{-27}$ erg sec, which is in close agreement with the value obtained by Max Planck in 1900 ($6.55 \times 10^{-27}$ erg sec). Planck was awarded the Nobel Prize in physics 1918 in recognition of the services he rendered to the advancement of physics by his discovery of energy quanta, whereas Millikan in 1923 for his work on the elementary charge of electricity and on the photoelectric effect.

Meanwhile, Einstein published a paper entitled "Zur Quantentheorie der Strahlung" (On the quantum theory of radiation) [5]. He described the emission and absorption process of single light quantum in two-level transitions in molecules, and discussed the probability coefficients for the spontaneous emission, induced emission and absorption. This theory with so-called Einstein's A and B coefficients became of great importance to help develop the theoretical background for the invention of lasers in the latter half of the 20th century.

Moreover, in this paper he showed that the momentum (recoil) $p$ of a light quantum with energy $E$ is equal to $E/c$, that is

$$p = E/c = h\nu/c = h/\lambda \tag{3}$$

where $c$ is the light velocity and $\lambda$ is the light wavelength in vacuum, respectively. However, this corpuscular concept of radiation again was not accepted easily and remained as a hypothesis for several years. It was Arthur H. Compton's experiment, which gave a solid empirical foundation for Einstein's quantum-corpuscular view of radiation.

The Compton effect is the increase of wavelength of an X-ray that has been scattered by electron. This change in wavelength is greater when the scattering angle of X-ray is larger. In 1923, Compton published a full discussion of the effect [6]. He assumed that each quantum of incident X-ray energy is concentrated in a single particle and acts as a unit onto a single electron. Then the electron recoils and a new energy quantum is generated for the scattered X-ray. On the basis of this quantum-corpuscular assumption and the conservation principles of energy and momentum with the aid of Eq. (3) and the theory of relativity, he was able to obtain the famous formulae, which splendidly explained all the experimental results. Compton's contribution to the proof of Einstein's quantum hypothesis of radiation is enormous, and he was awarded the Nobel Prize in physics 1927 for his discovery of wavelength change in diffused X-rays.

Einstein's idea of corpuscular view of light quantum also stimulated Louis de Broglie towards his idea of material wave associated with electron and other particles proposed in 1924 in his doctoral thesis. Although the process by which he induced the concept of de Broglie wave is very complicated [7], the final result of his idea is very simple and the same as Eq. (3), that is

$$p = h/\lambda, \; E = h\nu \tag{4}$$

where $p$ and $E$ are the momentum and the energy of electron, respectively, $\lambda$ is the wavelength and $\nu$ the frequency of the material wave associated with the electron. Thus, the duality, the corpuscular nature and the undulatory nature of both light wave and electron particle are combined by the above simple and symmetrical formulae of Einstein-de Broglie's relationship. It is clear that Einstein's particle theory of light and de Broglie's wave theory of particles both urged the progress of modern quantum mechanics, especially the wave mechanics by Erwin Schroedinger. In 1929 de Broglie was awarded the Nobel Prize in physics for his discovery of the wave nature of electron.

So far I have not used the term "photon" in honor of chronological order of events described in the above text. It may be noteworthy to point out here that the term "photon" was first proposed by G. N. Lewis in 1926 [8].

## 4. APPLICATION OF EXTERNAL PHOTOELECTRIC EFFECT

Let us now move on to the discussions on the application of Einstein's photoelectric theory to science and technology in human life.

The phototube (or photoelectric cell) is a simplest form of device based on the photoelectron emission. It consists of a photosensitive cathode and an output anode in vacuum. From Eq. (2), the longest wavelength of light in photoemission from the cathode with a work function $W$ (or $\phi$ in units of volt) is calculated as

$$\lambda_{max} = hc/q\phi \cong 1.24\,[\mu\mathrm{m}\cdot\mathrm{V}]/\phi \tag{5}$$

where $q$ is the electronic charge. For monochromatic light with $\lambda$ shorter than $\lambda_{max}$ and power $L$, the anode current is given as

$$I = \eta q L / h\nu \tag{6}$$

where $\eta$ is the quantum efficiency ($\leq 1$), which depends on $\lambda$.

Phototubes were commercialized in 1920s and 1930s and various kinds of photocathode materials with lower work functions were developed for visible and near-infrared light detection. The most popular application of that time was undoubtedly the sound motion picture, which was invented around 1923 by Lee De Forest, also an inventor of the triode vacuum tubes. In this synchronized sound system, the electrical signal of sound was converted to an optical signal and recorded on the sound track on the edge of film. The transmitted light power in the projector was detected by a phototube, amplified by triodes and converted back to sound in loud speakers. This talkie movie explosively spread over the world from 1927. It is a very interesting contrast that the most immediate appli-

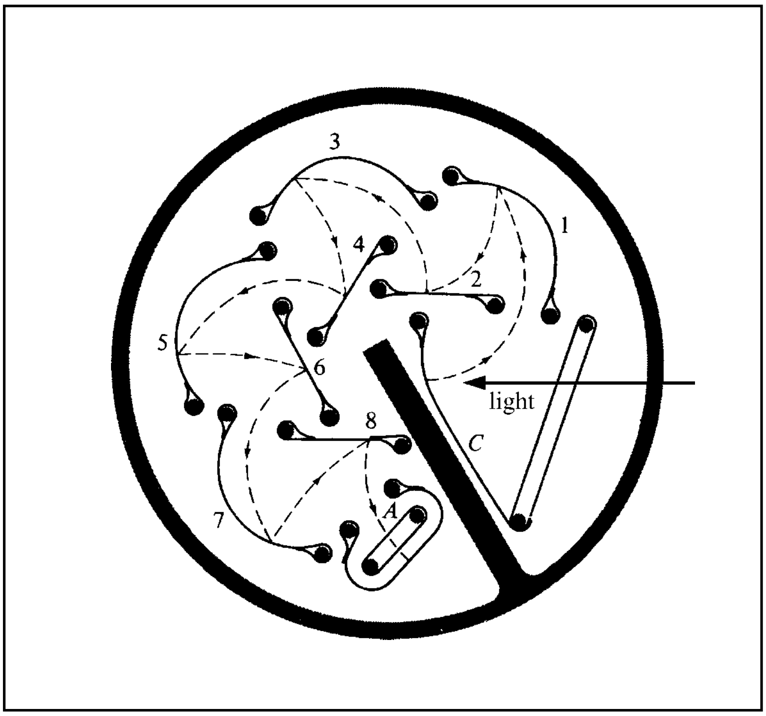


*Fig. 1: Schematic diagram of a photomultiplier tube. (Modified from an original figure shown in the following book: A. H. Sommer, Photoemissive materials: preparation, properties, and uses, Wiley, 1968.)*

cation of the photoelectric effect was to the most popular entertainment for mass members of the community, while the effect was still in academic dispute in the physics community.

Around 1931, Tsunetaro Kujirai of the Department of Electrical Engineering, the University of Tokyo, succeeded in the "optical telephony" in free space over 2km of distance in downtown Tokyo in daylight condition. The light source was a small incandescent lamp. Its current was modulated so that its output light power could be modulated in analog according to voice signal. At the receiver end, a special circuit with double phototubes was devised for high-sensitivity detection of weak light. This was believed to be the first research on optical communications in Japan.

The photomultiplier tube (PMT) is a phototube integrated with a structure for the current multiplication based on secondary emission of electrons. As illustrated in Fig. 1, it has a set of auxiliary electrodes called the dynodes (1~8) in between the photocathode (C) and anode (A) placed in vacuum. The dynodes are kept at progressively higher voltages with respect to the cathode, with a typical voltage step of 100V. A photoelectron emitted from the cathode bombards the dynode 1 and release a number of new electrons by secondary emission. This process takes place repeatedly at each dynode until the initial cathode current is amplified by a very large factor. If the average secondary emission multiplication factor at each dynode is $\delta$ and the number of dynodes is $N$, the total current multiplication factor is

$$G = \delta^N \qquad (7)$$

which gives $G \cong 1.7 \times 10^6$ for typical values of $\delta = 6$ and $N = 8$. Because such an ultra-high sensitivity for light detection is possible, these bulky and fragile vacuum tubes requiring high voltage sources are still in wide use in various fundamental researches today. Even detecting a single photon is possible if the tube is cooled thereby reducing the dark currents.

In 2002, Masatoshi Koshiba received the Nobel Prize in physics for his pioneering work on the birth of neutrino astronomy. The observation of supernova neutrinos and solar neutrinos was achieved with Kamiokande (Kamioka Nucleon Decay Experiment). The Kamiokande detector is basically a huge 3000ton water tank located 1000m deep in Kamioka mine near the Northern Alps in central Japan [9]. A total of 1,000 PMTs with an aperture diameter of 50 cm each, developed by Hamamatsu Photonics K. K., were mounted on the inner surface of the tank. Cherenkov radiation in water resulting from extremely rare neutrino-electron scattering was successfully detected by using PMTs in 1987 for the first time. In the second generation of Super-Kamiokande system built in 1996, the tank volume was upgraded to 50,000 $m^3$ and 11,146 PMTs were installed on the inner surface. This monstrous eye for elementary particle physics has a giant retina (inner surface) with a coverage ratio of photo-sensitive area up to 40 %.

An apparatus for PES (photoelectron spectroscopy or photoemission spectroscopy) is also a big machine, which sometimes occupies a beam-line of synchrotron radiator. The fundamental principle is based on the Einstein's photoelectric equation (2) in Sec. 2. If the surface of a solid is excited by monochromatic photon with energy of $h\nu$ and counts of photoelectrons are measured as a function of kinetic energy of photoelectron, detailed information on *W* can be obtained. In other words, the state density of electrons at the initial level from which the photoelectron originates can be measured as a function of electron energy.

Recently, hard X-ray photoelectron spectroscopy (HX-PES) has been developed by using SPring-8 synchrotron radiation facility in Japan [10]. The excitation by high-energy X-ray photon of 6 keV results in a larger probing depth of photoelectrons compared with the conventional PES, and enables to probe the intrinsic electronic properties of materials with minimum influence of surface condition. The valance band electronic structures of Si, GaAs, GaN, etc. have recently been reported.

## 5. APPLICATION OF INTERNAL PHOTOELECTRIC EFFECT

It is rather surprising that the internal photoelectric effect found in 1873 was much earlier than the discovery of external photoelectric effect made in circa 1888. It was discovered in the photoconduction of crystalline selenium by Willoughby Smith [11]. In the same year, R. E. Sale carried out more detailed following-up experiments and found some dependence of the effect on light wavelength [12]. It is very interesting that they used a gas-burner lamp and an electric arc lamp as the light source in some of their experiments, and that the telegraph engineers who were among the first generation of electrical engineers at the time, were very active in carrying out the fundamental research.

However, such photoconductive effect in semiconductors had scarcely been utilized in any applications for a long time. In the meantime, from 1920s through the 2nd World War era, theoretical solid-state physics made a rapid advance on the basis of quantum mechanics, which included the energy band theory of solids, band model of semiconductors, and rectification theory in semiconductor contacts. Finally all of a sudden, a major breakthrough was achieved in 1947 when a point contact bipolar transistor was invented (or rather discovered) at AT&T Bell Laboratories. Hereafter, various kinds of semiconductor electronic and photonic devices were invented and developed at a tremendous speed [13].

The photodiode (PD) is one of such novel devices developed from 1950s. It is based on the photoconduction across a reverse-biased pn or pin junction in semiconductors, or metal-semiconductor Schottky contact. The photocurrent is governed by the same Eq. (6) given for the phototube. The best feature of this device is the high speed response owing to a very small distance (a micrometer or so) for the carrier transit and small junction (or contact) capacitance. Today, the optical fiber communication is the dominant work force in telecommunications. The highest bit rate of optical pulses per wavelength channel used in practice is 40 Gb/s, and the shortest pulse width is around 10 ps ($10^{-11}$s). There is no difficulty in converting such a short optical pulse into an electrical pulse at the receiver end by using a high-speed photodiode.

The avalanche photodiode (APD) appears to be first proposed by K. M. Johnson in 1964 [14]. It is a photodiode operated at high reverse-bias voltages where current amplification via avalanche multiplication takes place. Initial photo-generated charged carriers are accelerated by a large electric field and bombard with the valance electrons thereby creating new carrier pairs of electrons and holes, and this process repeats. Through this avalanche multiplication of carriers, the current can be amplified by a factor of 100 if a proper bias voltage just slightly below the avalanche breakdown voltage is applied safely. The APD is also widely employed in a variety of applications requiring a high sensitivity and moderately high speed.

The phototransistor is another kind of photodetector device with a current amplification factor of 100. Basically it is a junction bipolar transistor whose base region is just floating (not connected to external circuit). Under a proper bias voltage applied between the emitter and collector, the base-collector junction comes to a normal reverse-bias state and the initial photocurrent generated near the junction can be internally amplified by a factor of $1/(1-\alpha)$ where $\alpha$ (typically 0.99) is the current transfer ratio from the emitter to collector. Although the speed is lower compared with APD, the phototransistor is the most popular photodetector because of much easier handling of operation and lower price.

Now let me review the photovoltaic effect, a special kind of photoconductive effects in semiconductors, which was discussed systematically by K. Lehovec for the first time in 1948 [15]. Under light illumination, semiconductor pn junction diodes can generate forward voltage by separation of optically generated electron-hole pairs under the built-in field of carrier depletion layer. The p-type region is charged positive and n-type negative. The direction of current flow to produce and maintain the above polarization is the same as that of current flow in the reverse-bias condition in dark. Therefore, this photovoltaic cell works as an electric cell from which electricity can be supplied to an external load. Figure 2 visualizes the above somewhat complicated situation of photovoltaic effect, where $E_{Fe}$ is quasi-Fermi level of electrons, $E_{Fh}$ is that of holes, $\phi$ is the diffusion potential difference between the n-type and p-type region in dark, and $V$ is the forward voltage generated by the photovoltaic effect.

This kind of photovoltaic cell is used as a simple photodetector with no electrical power supply necessary for its operation, but of course, the most important application is solar cell whose significance is discussed in a recent issue of the AAPPS Bulletin [16].

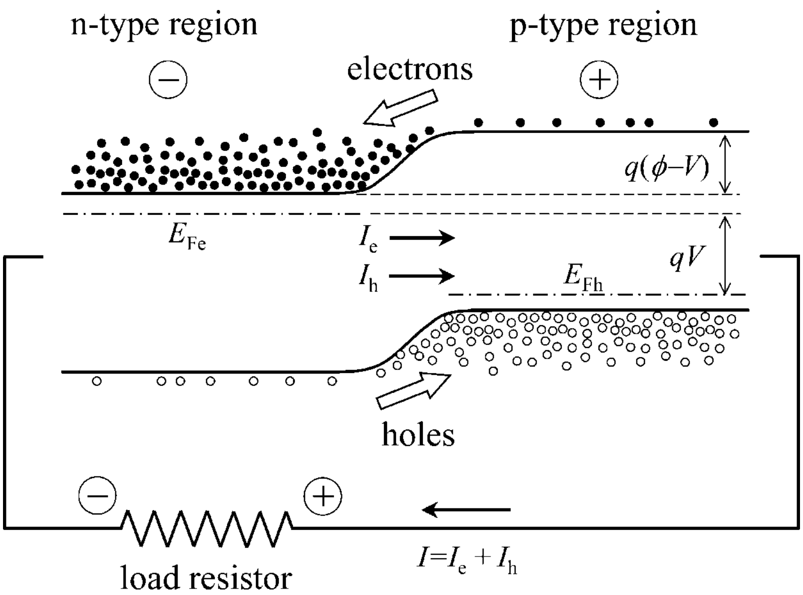


*Fig. 2: Illustration showing the principle of the photovoltaic effect in a semiconductor pn junction.*

In the past there existed a variety of vacuum tube image sensors in which the optical images can be transduced to serial electrical video signals. The main users of these devices were the professionals. In our present era of information and communication technology (ICT), solid-state image sensors represented by the charge coupled device (CCD) imagers are growing rapidly and becoming “ubiquitous” in our daily life, in mobile phones, in digital cameras, and so forth.

The CCDs were proposed by W. S. Boyle and G. E. Smith in 1970 [17]. In a CCD image sensor, the photo-generated minority carrier charge is stored at the Si-$SiO_2$ interface of a metal-oxide-semiconductor (MOS) capacitor, which corresponds to a part of a tiny pixel for 2-dimensional imaging. The charge is then transferred laterally along the interface, and is read out serially. The device with the highest spatial resolution commercially available today has 16M(mega) pixels.

Finally, I would like to introduce an interesting device which seems to be promising but not well known outside of high energy physics community. This is the hybrid photodiode (HPD), a vacuum photoelectric tube in which the anode is replaced by a reverse-biased planar silicon diode [18]. The photoelectrons emitted from the cathode are accelerated by an applied voltage of several kV and dissipate their kinetic energy in the silicon diode near the input surface. During this process, valence electrons in silicon are excited and electron-hole pairs are freed at the rate of one pair for every 3.6 eV of energy loss by the photoelectron. These carriers increased by electron-bombarded multiplication are efficiently collected by the reverse-biased diode, and the current amplification of a factor of 1000 can be obtained. This kind of dissipative gain due to electron-bombardment results in much less fluctuation than the gains associated with the secondary emission multiplication and avalanche multiplication. Therefore this device is less noisy and highly sensitive. Recently, an improved device is realized in which the diode is replaced by a multipixel ($8\times8$) avalanche diode having additional gain factor of 21 in tandem [19]. Strictly speaking, these novel devices are dominantly based on the external photoelectric effect and should be described in the previous section. For the sake of convenience, this device is introduced in this paragraph following the PD and APD devices.

## 6. CONCLUSION

In celebration of the World Year of Physics 2005, Einstein’s photon hypothesis proposed exactly a hundred years ago and its enormous impact on science and technology still lasting over a century, are reviewed from the viewpoint of applied physics and electronic engineering. In the first half of the article, the photon hypothesis and the law of photoelectric effect and their impact on the progress of modern physics are discussed. The latter half reviews the application of these theories mainly to photodetection devices with emphasis on the historical evolution of the new technologies.

It is evident that Einstein's photon hypothesis and the law of the photoelectric effect have exerted a great impact not only on physics but also on electronics, optics, optoelectronics (electro-optics), photonics, and many other branches of science and technology, and that the works of Einstein will continue to make a great impact in the future as well.

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