8. CORPUSCULAR AND QUANTUM OPTICS

I do not know what I may appear to the world, but to myself
I seem to have been only like a boy playing on the sea-shore,
and diverting myself in now and then finding a smoother pebble
or a prettier shell than ordinary, whilst the great ocean
of truth lay all undiscovered before me.

Isaac Newton

8.1. Discreteness of Nature

The Ancient Greek philosopher Democritus (Fig. 8.1) believed that everything is composed of "atoms", which are indivisible, differ in shape and size, and have always been in motion in empty space.

Rene Descartes filled the empty space with the smallest indistinguishable particles of aether. The concept of aether was used to explain such phenomena as the traveling of light and gravity. Isaac Newton tried to explain gravity with the help of condensation and rarefaction of particles of aether in empty space. To explain the interaction of bodies at a distance, Michael Faraday introduced the concept of the field created by these bodies. James Maxwell, in the framework of his theory of electromagnetism, showed that aether is not needed for the propagation of light.

Albert Einstein noted that the empty space between objects has its own physical properties and can be regarded as aether. Some scientists believe that there is no matter, that is, there are no elementary particles or atoms, but only various clots of aether exist.

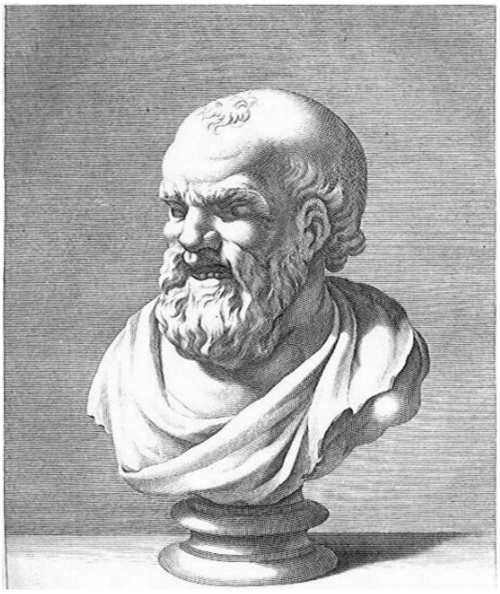

Fig. 8.1. The Ancient Greek philosopher Democritus (460–370 BC)

Isaac Newton (Fig. 8.2) was a genius of natural philosophy – a brilliant mathematician, physicist and astronomer. In 1687, Newton's book «*Mathematical Principles of Natural Philosophy*» was published. This book describes the laws of mechanics and their application to the theory of gravity and astronomy. Newton's laws became the basis of classical mechanics.

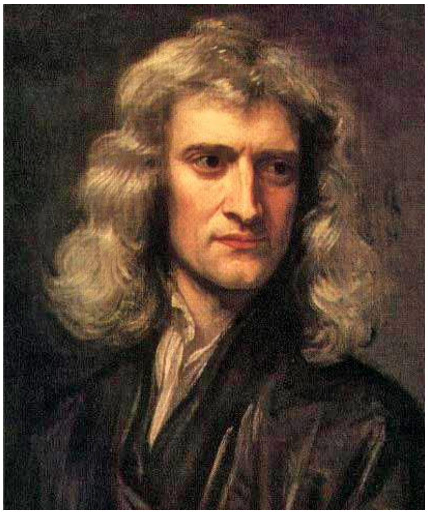

Fig. 8.2. The English natural philosopher Isaac Newton (1643–1727)

A very strong influence on the development of optics was made by Newton's «*Opticks*», published in 1704 [8.1]. Newton made in this book a bold assumption that light is not a continuous fluid of energy, but a discrete flow of particles – corpuscles. Newton tried to attribute to the corpuscles properties that would be consistent with the known phenomena of reflection and refraction of light, its diffraction and polarization.

Newtonian «Opticks» begins with the phrase:

«By the rays of light I understand its least parts, and those as well successive in the same lines, as contemporary in several lines».

Two centuries later, those properties that proved the wave nature of light were attributed to Newton's corpuscles. This was done in 1905 by Albert Einstein, proposing the concept of wave-particle duality of light. Since that time, light could be considered both a wave and particles. In free space, it is easier to consider light as a wave, and when interacting with matter, as particles.

In 1802, the German chemist, physicist and philosopher Johann Ritter (Fig. 8.3) decided to test the effect of various sections of the solar spectrum on silver chloride (AgCl), a salt that is sensitive to light and is currently used in photoemulsions. When illuminated, the salt turns black and decomposes into metallic silver and chlorine (gas). Ritter found that the most powerful effect on salt is exerted by the invisible part of the spectrum, which lies in front of the violet part. So was discovered ultraviolet radiation. Two years before, a study of the solar spectrum using a sensitive thermometer was carried out by Herschel, but the area of invisible radiation lying behind the red area caused the greatest heat. Thus, infrared radiation was discovered.

Fig. 8.3. The German scientist Johann Ritter (1776–1810)

The hypothesis of discreteness of electricity was put forward in 1801 by J. Ritter. In 1897, the English physicist Joseph Thomson, studying the deflection of cathode rays by electric and magnetic fields, showed that the rays consist of negatively charged particles («corpuscles») with a mass 1837 times smaller than the mass of the hydrogen atomю He also found the ratio of the electric charge of the particle to its mass (*e*/*m*). The charge-to-mass ratio turned out to be independent of the cathode material.

In 1899, Thomson conducted similar experiments with photoelectric particles emitted by an electrode under the action of light, and revealed their identity with particles of cathode rays (Fig. 8.4). The term "electron" to denote the electric charge of a monovalent ion in electrolysis was proposed in 1891 by the Irish physicist George Stoney, who in 1874 calculated the value of this charge. From the beginning of the 20th century this term was called not the elementary charge, but the particle itself.

For the discovery of the electron, the first subatomic particle, Joseph Thomson in 1906 was awarded the Nobel Prize in physics.

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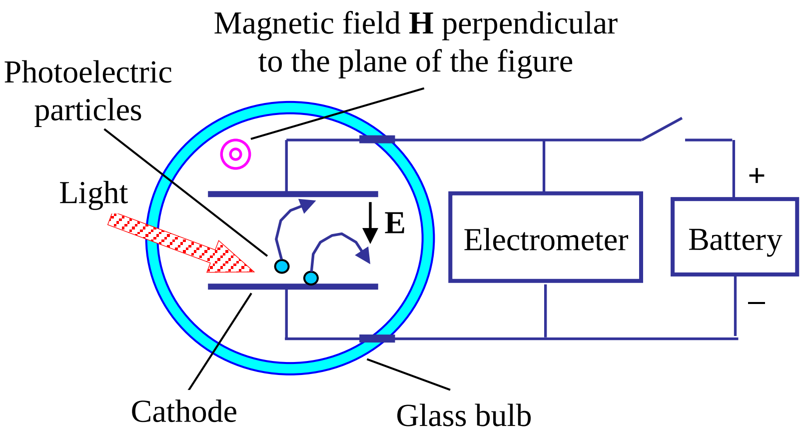

b

Fig. 8.4. The English physicist Joseph Thomson (1856–1940, *a*) and his experiment to determine ratio *e*/*m* (*b*)

8.2. Photoelectric Effect

Fig. 8.5. The German physicist Heinrich Hertz (1857–1894)

Maxwell showed that a change in the electric or magnetic field should lead to the formation of an electromagnetic wave. The first who experimentally confirmed the existence of electromagnetic waves was the German physicist Heinrich Hertz (Fig. 8.5).

In the years 1886–1889, Hertz investigated the phenomenon of electromagnetic induction. To do this, he used a Ruhmkoff coil, something like a transformer with a small number of turns of the primary winding and a very large number of turns of the secondary winding. A direct current is passed through the primary winding and, at the moment of its switching off, a high-voltage pulse is generated at the output of the secondary winding. With a small gap between the ends of the secondary winding, a spark jumps between them, caused by an electrical breakdown of air.

Hertz noted that in sunlight, the spark gap can be increased if the light is not passed through ordinary glass, but through quartz, which has greater transparency for ultraviolet rays. So in 1887, the photoelectric effect was discovered, which, however, was not very interested for Hertz. A much more important discovery awaited him.

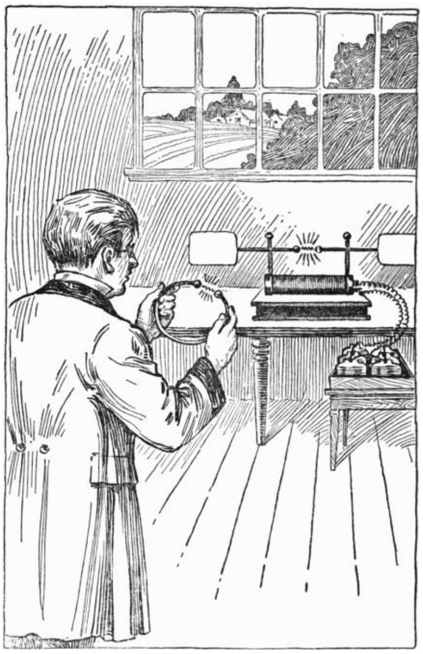

Fig. 8.6. Experimental proof of the existence of electromagnetic waves by Heinrich Hertz

Exploring electromagnetic induction, Hertz realized that he could experimentally prove the existence of electromagnetic waves.

Having bent the wire in the form of a ring, Hertz discovered that sparks flash in the gap between the ends of the wire, synchronously with the sparks in the secondary winding of the Ruhmkoff coil. By attaching metal rods to the terminals of the secondary winding, Hertz formed an antenna that made it possible to observe sparks in the gap of the ring from a distance of several meters (Fig. 8.6). The radio waves emitted by the Hertz transmitter had a frequency of approximately 50 MHz. Hertz discovered that some materials transmit these waves, and some reflect them.

The photoelectric effect could be discovered by an English physicist of German origin Arthur Schuster (Fig. 8.7), who in the same 1887 observed an accelerated discharge of an electrically charged body when sparks were created nearby. Schuster probably did not know that a strong ultraviolet component was present in the emission spectrum of the spark.

Schuster proved that the conductivity of gases is caused by the presence of ions in them and suggested that the collision of ions with a metal surface causes the appearance of cathode rays. The concept of "ion" was previously introduced into physics by Michael Faraday to designate particles of an unknown nature, which were moved between the electrodes when current flowed through the electrolyte.

Exploring the solar eclipses, Schuster determined that the period of solar activity is 11 years. As it turned out, grapes harvests have the same periodicity.

The scientist predicted the existence of antimatter, and when Thomson discovered the electron, he suggested that the electrons should be part of an atom. Schuster wrote a wonderful book on optics, where he analyzed in detail various optical phenomena [8.2].

The photoelectric effect discovered by Hertz is called the external photoelectric effect or *photoelectron emission*. With an external photoelectric effect, photons knock electrons out of the material. But at that time, Hertz did not know anything about the electron or the photon. Photoelectron emission is used in very sensitive photodetectors – photoelectronic multipliers.

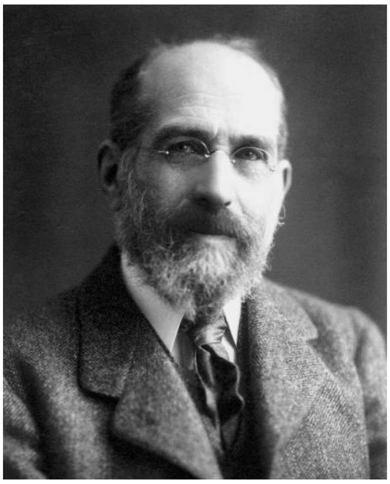

Fig. 8.7. The English scientist Arthur Schuster (1851–1934)

There is also an internal photoelectric effect in which photons absorbed by a material change its conductivity or form in it two volume electric charges of opposite sign. The first effect is photoconductivity, which is used in cheap inertial photodetectors – photoresistors. The second effect is a photogalvanic (or photovoltaic) effect discovered in 1839 by the nineteenth-years-old French physicist Edmond Becquerel during experiments with electrolyte and electrodes. The photovoltaic effect is used in the most sensitive and fastest semiconductor photodetectors – photodiodes. Almost sixty years later, in 1896, his son Henri Becquerel discovered the phenomenon of radioactivity.

8.3. The quantum nature of the photoelectric effect

In 1905, at the age of 26, the German-born theoretical physicist Albert Einstein (Fig. 8.8) published four papers, on the photoelectric effect, Brownian motion, special relativity, and the equivalence of mass and energy, which radically changed the face of physics.

After Thomson discovered the negatively charged corpuscles and established the discreteness of the electric current, after the hypothesis of Planck energy quanta appeared, Einstein suggested that the energy of the light flux does not just consist of energy quanta, as Planck thought, but is represented by the carriers of these quanta – particles or, as they were first called, light quanta. In 1923, Arthur Compton named them photons.

Einstein formulated the law of the photoelectric effect, which can be represented as an equation [8.3]

$$h\nu = W + \frac{m_e V_{\max}^2}{2},$$

where h is the Planck constant, ν is the frequency of light, W is the work function of the illuminated material, m_e is the electron mass, and $V_{\max}$ is the maximum velocity of the knocked out electron (so called photoelectron).

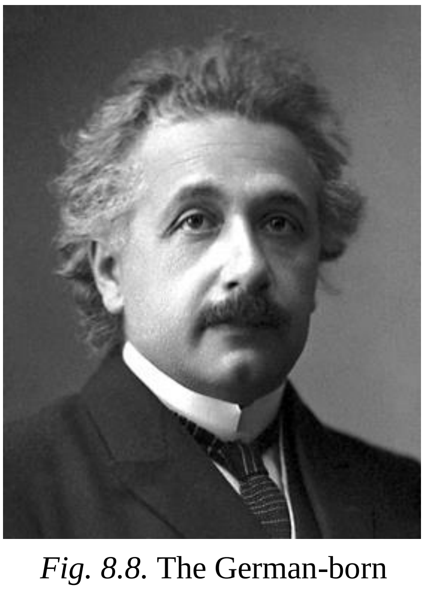

Fig. 8.8. The German-born physicist Albert Einstein (1879–1955)

Note that the work function W is not a characteristic of a bulk material, but rather a property of the surface of the material. The work function will be different for a clean surface of the material or having some kind of film (or contamination or specially applied coating). Crystal faces have different work function. It also depends on the temperature of the material.

In the table 8.1 are given as an example the work functions of several materials.

***Table 8.1.* The work functions of some materials**

Material	Cs	K	Al	Ag	W	Cu	Si	C	Au	Pt
W, eV	1.95	2.29	4.06–4.26	4.26–4.74	4.32–5,22	4.53–5.10	4.60–4.85	4.90–5.10	5.10–5.47	5.12–5.93

In electron tubes, the principle of which is based on the control of an electron beam, the electrons are emitted by the heated cathode. This process is called *thermionic emission*. The first cathodes were made of pure tungsten and the tungsten filament needed to be heated with current up to 2500 K. The development of oxide-coated filaments in the mid-1920s reduced the work function of W and enabled operation at a temperature of 1000 K.

Note that the work function is the kinetic energy of the electron inside the material, necessary to overcome the braking electric field of the surface double electric layer. This field holds electrons inside the material. If an opposite field is applied to the material, the work function decreases and *field emission* is observed.

In 1913, the American experimental physicist Robert Millikan (Fig. 8.9) published an article in which he described experiment on determining the charge of a corpuscle discovered by Joseph Thomson [8.4]. The essence of the experiment was to measure the velocity V of movement of small drops of oil in an electric field. After making many measurements, Millikan found that $V = Ke$, where K is always integer. This testified to the fact that the electric charge of the body always consists of identical minimum portions of charge e and the electron is the carrier of these minimal portions. Milliken found the charge of electron, and his value is only 1% different from the value obtained by modern methods. Thus, the properties of the first elementary particle became known,

$$e = 1.602 \cdot 10^{-19}\ \text{C}, \quad m_e = 9.109 \cdot 10^{-31}\ \text{kg},$$

which allowed the Danish physicist Niels Bohr to build an atom model in the same 1913.

In 1923, Robert Millikan was awarded the Nobel Prize in physics [8.5]. His experiments confirmed the existence of light particles (light quanta) and the validity of the Einstein law of photoelectric effect.

Fig. 8.9. The American physicist Robert Millikan (1868–1953)

Note that the size of the electron is still unknown. It was possible to see only his trace in the cloud chamber, devised in 1911 by the English physicist Charles Wilson. He found that a charged particle caused a condensation of supersaturated water vapor along its path.

Fig. 8.10. The American physicist Arthur Compton (1892–1962)

8.5. The mechanical action of a photon

The light quantum as a particle was finally recognized after the American physicist Arthur Compton (Fig. 8.10) discovered in 1922 the phenomenon of an increase in the wavelength of X-rays after its scattering by electrons (the Compton effect). From the point of view of wave theory, absorbed radiation causes forced oscillations of the electrons of matter and these vibrations are the cause of the appearance of scattered radiation. Obviously, the frequencies of both radiations would have to be equal, but in fact, in addition to the spectrally unbiased component, a component with a longer wavelength appears in the scattered radiation.

Compton showed that, based on the hypothesis of Einstein light quanta, when a photon interacting with an electron, the energy conservation and the momentum conservation conditions must be satisfied:

$$h\nu + m_e c^2 = h\nu' + m_e^* c^2,$$

$$\left(m_e^* V\right)^2 = \left(\frac{h\nu}{c}\right)^2 + \left(\frac{h\nu'}{c}\right)^2 - \left(\frac{2h^2}{c^2}\right)\nu\nu'\cos\theta,$$

where ν and ν' are the frequency of light before and after interaction, m_e^* is the relativistic mass of the electron, V is the electron velocity, and θ is the angle between the velocity vectors of the incident and scattered photons (Fig. 8.11). In deriving these conditions, Compton suggested that the initial velocity of the electron is zero, and its mass after collision with a photon changes in accordance with the relation

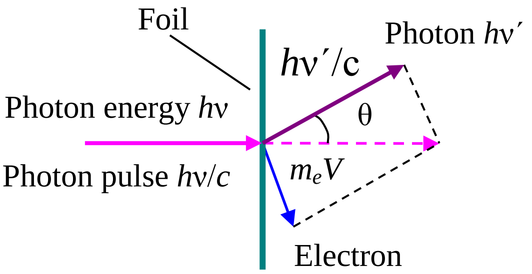

Fig. 8.11. Photon scattering on an electron present in a foil (Compton effect)

following from Einstein's special theory of relativity, namely

$$m_e^* = \frac{m_e}{\sqrt{1 - V^2/c^2}}.$$

The scattering of the light quantum by the electron at an angle θ to the initial propagation direction leads to a Compton shift of the light wavelength

$$\Delta\lambda = \frac{2h}{m_e c}\sin^2\frac{\theta}{2}.$$

For $\theta = \pi/2$, the wavelength shift reaches the maximum value of $\lambda_C = h/m_e c = 2.43 \cdot 10^{-12}$ m, called the Compton wavelength.

The Compton effect can be observed during the illumination of, for example, graphite, paraffin, very thin metal plates, but the photon energy must exceed the work function of this material at least a thousand times in order for the wavelength shift to be noticeable. That is why it is very difficult to observe this effect for visible radiation.

In 1923, Compton called the light quantum a photon, to emphasize that it is not just a portion of energy but an elemental particle. It should be noted that for some time physicists believed that the Compton effect cannot be explained within the wave theory, and this was the main argument in favor of the light quantum hypothesis. But if we consider the acceleration of an electron by a field of an electromagnetic wave and the simultaneous diffraction of this wave on a moving electron, then the Doppler effect also leads to a Compton shift of the frequency of this wave.

The Nobel prize in physics 1927 was divided equally between Arthur Compton "for his discovery of the effect named after him" and Charles Wilson "for his method of making the paths of electrically charged particles visible by condensation of vapour" [8.8].

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