The photoelectric effect with phonon emission

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Abstract

We egeneralize the relativistic energy relation for the photoelectric effect in case of the simultaneous emission of electrons and phonons in the metal medium.
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The photoelectric effect is a quantum electromagnetic phenomenon in which electrons are emitted from matter after the absorption of energy from electromagnetic radiation. Frequency of radiation must be above a threshold frequency, which is specific to the type of surface and material. No electrons are emitted for radiation with a frequency below that of the threshold. These emitted electrons are also known as photoelectrons in this context. The photoelectric effect was theoretically explained by Einstein in his paper (Einstein, 1905; 1965) and introduced the term "light quanta" called "photons" by chemist G. N. Lewis, in 1926. Einstein writes (Einstein, 1905; 1965): *In accordance with the assumption to be considered here, the energy of light ray spreading out from point source is not continuously distributed over an increasing space but consists of a finite* *number of energy quanta which are localized at points in space, which move without dividing, and which can only be produced and absorbed as complete units.*

The linear dependence on the frequency was experimentally determined in 1915 when Robert Andrews Millikan showed that Einstein formula

$$\hbar\omega = \frac{mv^2}{2} + W \tag{1}$$

was correct. Here $\hbar\omega$ is the energy of the impinging photon, v is electron velocity measured by the magnetic spectrometer and W is the work function of concrete material. The work function for Aluminium is 4.3 eV, for Beryllium 5.0 eV, for Lead 4.3 eV, for Iron 4.5 eV, and so on (Rohlf, 1994). The work function concerns the surface photoelectric effect where the photon is absorbed by an electron in a band. The theoretical determination of the work function is the problem of the solid state physics. On the other hand, there is the so called atomic photoeffect (Amusia, 1987; Berestetzky et al., 1989; Sauter, 1931; Stobbe, 1930), where the ionization energy plays the role of the work function. The system of the ionization energies is involved in the tables of the solid state physics. The work fuction of graphene, or, work fuction of the Wigner crystal (Wigner, 1936) in graphene was never determined, and it is the one of the prestige problem of the contemporary experimental and theoretical graphene physics and the Wigner crystal physics .

In case of the volume photoeffect, the ionization work function is defined in many textbooks on quantum mechanics. Or,

$$W = \int_{x_1}^{x_2} \left(\frac{dE}{dx}\right) dx \tag{2}$$

where E is the energy loss of moving electron.

The formula (1) is the law of conservation of energy. The classical analogue of the equation (1) is the motion of the Robins ballistic pendulum in the resistive medium.

The Einstein ballistic principle is not valid inside of the blackbody. The Brownian motion of electrons in this cavity is caused by the repeating Compton process $\gamma + e \to \gamma + e$ and not by the ballistic collisions. The diffusion constant for electrons must be calculated from the Compton process and not from the ballistic process. The same is valid for electrons immersed into the cosmic relic photon sea.

The idea of the existence of the Compton effect is also involved in the Einstein article. He writes (Einstein, 1905; 1965): *The possibility should* *not be excluded, however, that electrons might receive their energy only in part from the light quantum.* However, Einstein was not sure, a priori, that his idea of such process is realistic. Only Compton proved the reality of the Einstein statement.

At energies $\hbar\omega < W$, the photoeffect is not realized. However, the photo-conductivity is the real process. The photoeffect is realized only in medium and with low energy photons, but with energies $\hbar\omega > W$, which gives the Compton effect negligible. Compton effect can be realized with electrons in medium and also with electrons in vacuum. For $\hbar\omega \gg W$ the photoeffect is negligible in comparison with the Compton effect. At the same time it is necessary to say that the Feynman diagram of the Compton effect cannot be reduced to the Feynman diagram for photoeffect. In case of the high energy gamma rays, it is possible to consider the process called photoproduction of elementary particles on protons in LHC, or photo-nuclear reactions in nuclear physics. Such processes are energetically far from the photoelectric effect in solid state physics.

Eq. (1) represents so called one-photon photoelectric effect, which is valid for very weak electromagnetic waves. At present time of the laser physics, where the strong electromagnetic intensity is possible, we know that so called multiphoton photoelectric effect is possible. Then, instead of equation (1) we can write

$$\hbar\omega_1 + \hbar\omega_2 + ...\hbar\omega_n = \frac{mv^2}{2} + W. \tag{3}$$

The time lag between the incidence of radiation and the emission of a photoelectron is very small, less than 10^{-9} seconds.

As na analogue of the equation (3), the multiphoton Compton effect is also possible: $\gamma_1 + \gamma_2 + ...\gamma_n + e \rightarrow \gamma + e$ and two-electron, three-electron,... n-electron photoelectric effect is also possible (Amusia, 1987). To our knowledge the Compton process with the entangled photons was still not discovered and elaborated. On the other hand, there is the deep inelastic Compton effect in the high energy particle physics. Now, let us approach the basic theory of phonons.

A phonon is a collective excitation in a periodic, elastic arrangement of atoms or molecules in condensed matter, often designated a quasiparticle. It is an quantum mechanical excited state of the modes of vibrations of elastic structures of interacting particles. They play a major role in thermal conductivity and electrical conductivity. The concept of phonons was introduced in 1932 by Tamm. The long-wavelength phonons give rise to sound. The higher-frequency phonons are responsible for the majority of the thermal capacity of solids.

While waves phenomena in classical mechanics of solid state are only waves, phonons have particle-like properties too, in a way related to the wave particle duality of quantum mechanics.

Acoustic phonons are coherent movements of atoms of the lattice out of their equilibrium positions similarly to the acoustic waves. Displacement perpendicular to the propagation direction is comparable to waves in water. The acoustic phonons with thee infinity length correspond to a simple displacement of the whole crystal. Acoustic phonons exhibit a linear relationship between frequency and phonon wavevector for long wavelengths. Optical phonons are out-of-phase movements of the atoms in the lattice.

By analogy to photons and matter waves, phonons have been treated with wavevector k as though it has a momentum $\hbar\mathbf{k}$, however, this is not strictly correct, because $\hbar\mathbf{k}$ is not actually a physical momentum; it is called the crystal momentum or pseudomomentum. This is because $\mathbf{k}$ is only determined up to addition of constant vectors (the reciprocal lattice vectors and integer multiples thereof).

A phonon with wavenumber k is thus equivalent to an infinite family of phonons with wavenumbers (in the linear case) $k \pm 2/a, k \pm 4/a$, and so forth. Physically, the reciprocal lattice vectors act as additional amount of momentum which the lattice can impart to the phonon.

The thermodynamic properties of a solid are directly related to its phonon structure. The phonon density of states determine the heat capacity of a crystal. Because phonons are generated by the temperature of the lattice, they are sometimes designated thermal phonons.

The behavior of thermal phonons is similar to the photon gas produced by an electromagnetic cavity, wherein photons may be emitted or absorbed by the cavity walls. This similarity is not coincidental, for it turns out that the electromagnetic field behaves like a set of harmonic oscillators No doubt, that Einstein consiered such model in the determination of the heat capacity and Debye performed the brilliant determinantion of the Einstein model.

In thermal equilibrium and within the harmonic regime, the probability of finding phonons (or photons) in a given state with a given angular frequency is: $n(\omega) = 1/[\exp(\hbar\omega/k_B T) - 1]$, where ω is the frequency of the phonons (or photons) in the state, k_B is Boltzmann's constant, and T is the temperature. So, we are prepared to follow the way from Einstein to the photoelectric effect with phonon emission

Let us still remark that the imposibility of photon absorption by free electron can be demonstrated using the relativistic equations

$$\hbar\omega = \frac{mc^2}{\sqrt{1-\frac{v^2}{c^2}}} \tag{4}$$

and

$$\frac{\hbar\omega}{c} = \frac{mv}{\sqrt{1-\frac{v^2}{c^2}}}, \tag{5}$$

where eq. (5) is the expression of the conservation of momentum of the system pf particles photon and electron. After division of eq. (4) by eq. (5) ((4)/(5)), we get after elementary modfication $1 = c/v$, which is logical contradiction.

Now, let us consider the situation, where electron is located in some medium, where the Einstein work function is the necessary physical reality and the emission of phonon of the energy $\hbar\Omega$ is also the physical reality. Then instead of equations (4) and (5) we write

$$\hbar(\omega - \Omega) - W = \frac{mc^2}{\sqrt{1-\frac{v^2}{c^2}}} \tag{6}$$

and

$$\frac{\hbar\omega}{c} = \frac{mv}{\sqrt{1-\frac{v^2}{c^2}}} + P = \frac{mv + P\sqrt{1-\frac{v^2}{c^2}}}{\sqrt{1-\frac{v^2}{c^2}}}, \tag{7}$$

where we have introduced P as the momentum of phonon. After division of eq. (6) by eq. (7) ((6)/(7)), we get after elementary operations

$$\frac{\hbar(\omega - \Omega) - W}{\hbar\omega} = \frac{mc}{mv + P\sqrt{1-\frac{v^2}{v^2}}} \tag{8}$$

The last formula can be experimentally verified in the analogue with the Einstein formula.

At present time, the most attention in graphene physics is devoted to the conductivity of a graphene with the goal to invent new MOSFETs and new transistors for new computers. However, we do not know, a priori, how many discoveries are involved in the investigation of he photo-electric effects in graphene with simultaneous phonon emission.

The photoelectric process process in graphene given by with the following equation:

$$\hbar\omega + G \to G^- + e + \hbar\Omega, \tag{9}$$

where G is the graphene and the electron in the crystal is considered as the elementary particle with all atributes of electron as an elementary particle and not the pseudoelectron which can be also considered in the solid state physics. Pseudoelectron is the product of the crystalline medium and as a such it can move only in the medium. The existence of the psedoelectron in vacuum is not possible. However, the process where the photon interacts with the pseudoelectron in a medium and the pseudoelectron decays in such a way that the integral part of the decay product is also electron, is possible and till present time the theory of such process was not elaborated. The new experiments are necessary in order to verify the photoelectric equation in graphene.

The photoelectric effect at zero temperature can be realized only by very short laser pulses, because in case of the continual laser irradiation the zero temperature state is not stable. Only very short pulses can conserve the zero temperature of the 2D system.

The information on the photelectric effect in graphene and also the elementary particle interaction with graphene is necessary not only in the solid state physics, but also in the elementary particle physics in the big laboratories, where graphene can form the substantial components of the particle detectors. The graphene can be probably used as the appropriate components in the solar elements, the anode and cathode surfaces in the electron microscope, or, as the medium of the memory hard disks in the computers.

While the last century economy growth was based on the inventions in the Edison-Tesla electricity, the economy growth in this century will be obviously based on the graphene physics. We hope that these perspective ideas will be considered at the universities and in the physical laboratories.

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