The ultrasound photoelectric effect

Miroslav Pardy
Department of Physical Electronics
Masaryk University
Kotlářská 2, 611 37 Brno, Czech Republic
e-mail:pamir@physics.muni.cz

May 24, 2026

Abstract

The ultrasound photoelectric effect is the new phenomenon in particle physics. We derive the velocity of sound in the blackbody gas of photons. Derivation is based on the thermodynamic theory of the photon gas and the Einstein relation between energy and mass. The quantization of this sound forms the matter of phonons. The ultra-sound phonons composed from photons generate the photoelectric effect as the analogue to the Einstein photoelectric effect in metals. The application of this effect in the elementary particle physics, atomic physics and nuclear physics is not excluded.

1 Introduction

Ultrasound is defined by the American National Standards Institute as ”sound at frequencies greater than 20 kHz”. In air at atmospheric pressure, ultrasonic waves have wavelengths of 1.9 cm or less. Ultrasound can be generated at very high frequencies. Ultrasound in sonochemistry is used at frequencies up to multiple hundreds of kilohertz. Medical imaging equipment uses frequencies in the MHz range. UHF ultrasound waves have been generated as high as the gigahertz range.

Power ultrasound in chemistry does not interact directly with molecules to induce the chemical change, as its typical wavelength (in the millimeter range) is too long compared to the molecules. Instead, the energy causes cavitation which generates extremes of temperature and pressure in the liquid where the reaction happens. Ultrasound also breaks up solids.

The photoelectric effect is a new quantum electronic 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 using the light quanta. Einstein (1905) writes: *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 effect is also termed as the Hertz effect due to its discovery by Heinrich Rudolf Hertz in 1887. The Stoletov effect, the Edison effect, the Tesla effect, the Lenard effect was also used in the past. However, at present time, such terminology is not used in the modern textbooks.

It is known some prehistory of the photoelectric effect beginning by 1839 when Alexandre Edmond Becquerel observed the photoelectric effect via an current when an electrode was exposed to light. Later in 1873, Willoughby Smith found that selenium is photoconductive.

In 1905 it was known that the energy of the photoelectrons increased with increasing frequency of incident light, but the linear dependence on the frequency was experimentally determined in 1915 when Robert Andrews Millikan showed that Einstein formula

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

was correct. Here $\hbar\omega$ is the energy of the impinging photon and A is 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), 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 formula (1) is the law of conservation of energy. The energy of the photon is absorbed by the electron and, if sufficient, the electron can escape from the material with a finite kinetic energy. If the electromagnetic wave is weak then a single photon can only eject a single electron, as the energy of one photon may only be absorbed by one electron (the principle "all, or nothing").

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): *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 priory, that his idea of such process is realistic. Only Compton proved the reality of the Einstein statement.

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

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

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 (2), the multiphoton Compton effect is also possible:

$$\gamma_1 + \gamma_2 + ...\gamma_n + e \to \gamma + e, \tag{3}$$

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.

The Einstein equation (1) appeared in his paper named "On a Heuristic Viewpoint Concerning the Production and Transformation of Light". This paper proposed the simple description of "light quanta" called "photons" by chemist G. N. Lewis, in 1926. Later Compton, in his famous experiment proved that light quanta have particle properties, or, photons are elementary particles. On the other hand, photons are still mysterious objects and nobody knows everything about photons.

2 Sound in the blackbody

The Planck distribution was derived in 1900 (Planck, 1900; Schöpf, 1978). The Planck heuristic derivation was based on the investigation of the statistics of the system of oscillators.

Later Einstein (1917) derived the Planck formula from the Bohr model of atom. Bohr created two postulates which define the model of atom: 1. every atom can exist in the discrete series of states in which electrons do not radiate even if they are moving at acceleration (the postulate of the stationary states), 2. transiting electron from the stationary state to other, emits the energy according to the law $\hbar\omega = E_m - E_n$, called the Bohr formula, where E_m is the energy of an electron in the initial state, and E_n is the energy of the final state of an electron to which the transition is made and $E_m > E_n$.

Einstein introduced coefficients of spontaneous and stimulated emission A_{mn}, B_{mn}, B_{nm}. In case of spontaneous emission, the excited atomic state decays without external stimulus as an analog of the natural radioactivity decay. Later, quantum theory (Berestetzkii et al., 1989; Davydov, 1973; Drukarev, 1988) explained rigorously the process of spontaneous emission. The energy of the emitted photon is given by the Bohr formula. In the process of the stimulated emission the atom is induced by the external stimulus to make the same transition. The external stimulus is a blackbody photon that has an energy given by the Bohr formula.

The Planck power spectral formula is as follows (Rohlf, 1994):

$$P(\omega)d\omega = \hbar\omega G(\omega)\frac{d\omega}{\exp\frac{\hbar\omega}{k_BT} - 1}; \quad G(\omega) = \frac{\omega^2}{\pi^2 c^3}, \tag{4}$$

where $\hbar\omega$ is the energy of a blackbody photon and $G(\omega)$ is the number of electromagnetic modes inside of the blackbody, k is the Boltzmann constant, c is the velocity of light, T is the absolute temperature.

The internal density energy of the blackbody gas is given by integration of the last equation over all frequencies ω, or

$$u = \int_0^\infty P(\omega)d\omega = aT^4; \quad a = \frac{\pi^2 k^4}{15\hbar^3 c^3}. \tag{5}$$

In order to understand the derivation of speed of sound in gas and in the relic photon sea, we start with the derivation of the speed of sound in the real elastic rod (Pardy, 2013).

Let A be the cross-section of the element Adx of a rod, where dx is the linear infinitesimal length on the abscissa x. The $\varphi(x,t)$ let be deflection of the element Adx at point x at time t. The shift of he element Adx at point $x + dx$ is evidently

$$\varphi + \frac{\partial\varphi}{\partial x}dx. \tag{6}$$

The relative prolongation is evidently $\partial\varphi(x,t)/\partial x$. The differential equation of motion of the rod can be derived by the following obligate way. We suppose that the force tension $F(x,t)$ acting on the element Adx of the rod is given by the Hook law:

$$F(x,t) = EA\frac{\partial\varphi}{\partial x}, \tag{7}$$

where E is the Young modulus of elasticity, A is the cross section of the rod. We easily derive that

$$F(x+dx) - F(x) \approx EA\frac{\partial^2\varphi}{\partial x^2}dx \tag{8}$$

The mass of the element Adx is ϱAdx, where ϱ is the mass density of the rod and the dynamical equilibrium is expressed by the Newton law of force:

$$\varrho A dx \varphi_{tt} = EA\varphi_{xx} dx \tag{9}$$

or,

$$\varphi_{tt} - v^2\varphi_{xx} = 0, \tag{10}$$

where

$$v = \left(\frac{E}{\varrho}\right)^{1/2} \tag{11}$$

is the velocity of sound in the rod.

The complete solution of eq. (10) includes the initial and boundary conditions. We suppose that the velocity law (11) involving modulus of elasticity and mass density is valid also for gas intercalated in the rigid cylinder tube. According to the definition of the Young modulus of elasticity where $(\Delta L/L)$ is the relative prolongation of a rod, we have as an analogue for the tube of gas $\Delta V/V$, $F \to \Delta p$, where V is the volume of a gas and p is pressure of a gas. Then, the modulus of elasticity is defined as the analogue of eq. (7). Or,

$$E = -\frac{dp}{dV}V. \tag{12}$$

The process of the sound spreading in ideal gas is the adiabatic thermodynamic process with no heat exchange. We use it later as a model of the sound spreading in the gas of blackbody photons. Such process is described by the thermodynamical equation

$$pV^{\kappa} = const, \tag{13}$$

where κ is the Poisson constant defined as $\kappa = c_p/c_v$, with c_p, c_v being the specific heat under constant pressure and under constant volume.

After differentiation of eq. (13) we get the following equation

$$dpV^{\kappa} + \kappa V^{\kappa-1}dV = 0, \tag{14}$$

or,

$$\frac{dp}{dV} = -\kappa\frac{p}{V}. \tag{15}$$

After inserting of eq. (15) into eq. (12), we get from eq. (11) for the velocity of sound in gas the so called Newton-Laplace formula:

$$v = \sqrt{\kappa\frac{p}{\varrho}}, \tag{16}$$

where ϱ is the mass density of gas.

The density of the equilibrium radiation is given by the Stefan-Boltzmann formula

$$u = aT^4, ; \quad a = 7,5657.10^{-16}\frac{\mathrm{J}}{\mathrm{K}^4\mathrm{m}^3}. \tag{17}$$

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Then, with regard to the thermodynamic definition of the specific heat

$$c_v = \left(\frac{\partial u}{\partial T}\right)_V = 4aT^3. \tag{18}$$

Similarly, with regard to the general thermodynamic theory

$$c_p = c_v + \left[\left(\frac{\partial u}{\partial V}\right)_T + p\right]\left(\frac{\partial V}{\partial T}\right)_p = c_v, \tag{19}$$

because $\left(\frac{\partial V}{\partial T}\right)_T = 0$ for photon gas and in such a way, $\kappa = 1$ for photon gas. According to the theory of relativity, there is simple equivalence between mass and energy. Namely, $m = E/c^2$. At the same time, there is relation between pressure and the internal energy of the blackbody gas following from the electromagnetic theory of light $p = u/3$. So, in our case

$$\varrho = u/c^2 = \frac{aT^4}{c^2}; \quad p = \frac{u}{3}. \tag{20}$$

So, after insertion of formulas in equation (20) in to eq. (16), we get the final formula for the velocity of sound in three photon sea of the blackbody is as follows:

$$v = c\sqrt{\frac{\kappa}{3}} = \frac{c}{3}\sqrt{3}, \tag{21}$$

which is the result derived by Partovi (1994) using the QED theory applied to the photon gas. No energy signal can move with velocity greater than the speed of light. And we correctly derived $v/c < 1$.

So, we have seen in this section, that using the classical thermodynamical model of sound in the classical gas we can easily derive some properties of the blackbody gas, namely the velocity of sound in it and in the relic photon sea. It is not excluded that the relic sound can be detected by the special microphones of Bell laboratories. Let us still remark that if we use van der Waals equation of state, or, the Kamerlingh Onnes virial equation of state, the obtained results will be modified with regard to the basic results.

3 The phonon composed from the blackbody photons

Phonons are, according the definition, quantized sound waves, similar to photons as quantized light waves. The study of phonons is an important part of condensed matter physics. They play a major role in many of the physical properties of condensed matter systems, such as thermal conductivity and electrical conductivity, as well as play a fundamental role in models of neutron scattering and related effects. The concept of phonons was introduced in 1932 by Soviet physicist Igor Tamm.

In other words, a phonon is the quantum mechanical description of an elementary vibrational motion in which a lattice of atoms, or, molecules uniformly oscillates at a single frequency. In classical mechanics this designates a normal mode of vibration. Any arbitrary lattice vibration can be considered as a superposition of these elementary vibration modes which follow Fourier analysis. While normal modes are wave-like phenomena in classical mechanics, phonons have particle-like properties too, in a way related to the wave-particle duality of quantum mechanics. In our case, we consider the vibration of the blackbody

4 The photoelectric effect in the blackbody

We have considered the the Einstein photoelectric equation

$$\hbar\omega = \frac{mv^2}{2} + \mathcal{W} \tag{22}$$

in the blackbody. The energy $\hbar\omega$ is the energy of the ultrasound phonon which is composed from blackbody photons. The photons in ther blackbody phonon enable the electromagnetic interaction of phonon with ekectron and the validity of the Einstein photoelectric equation. The work function A is considered very small for the blackbody including electrons and it means that the incident energy of the ultrasound phonon is not necessary to be very large.

The work function $\mathcal{W}$ in the Einstein equation (22) was introduced at the blackbody situation phenomenologically and can be determined in the framework of QED methods. The new experiments ar necessary in order to verify the photoelectric equation in blackbody.

5 Discussion

The interaction of phonon with electron is of course substantially new process which will be obviously one of the future problem of the relativistic photon physics, or, the quantum optics, or, quantum electrodynamics.

The ultrasound photoelectric effect being beyond classical photoelectric effect can be generalized to blackbody electrons in a magnetic field which refer to two extreme astrophysical situations, namely, 1) an optically thin medium, and 2) an optically thick medium, where local thermodynamic equilibrium is set up and radiative heat transfer has to be considered. In the latter case, the scattering process and its dependence on frequency, direction, and polarization play an important role (Gnedin et al., 1974).

The information on the phono-electrical effect in blackbody is important not only in the solid state physics, but also in the elementary particle physics in the laboratories where phonons can form the substantial components of the particle detectors. The ultrasound phonon can be probably used as the appropriate components in the solar elements, the anode and kathode surface in the electron microscope, or, as the medium of the memory hard disks in the computers. We hope that these possibilities will be considered in the physical laboratories.

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