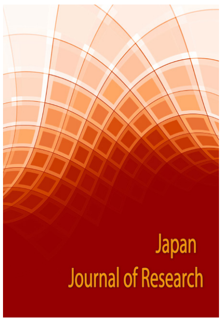
Japan Journal of Research

Review Article



The Quantum of Radiation or A Threshold of Action?

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• Received Date: 20 Feb 2026
• Accepted Date: 05 Mar 2026
• Publication Date: 10 Mar 2026

Keywords

classical and quantum mechanics, radiation law and Planck's constant, energy quantum and its universality, quantum yield and spectral sensitivity, performance characteristics, and efficiency of photocathodes.

Abstract

This article refutes the assertion, based on an examination of the photoelectric effect, that Planck's constant is universal, as well as the quantum mechanics that underlies it. Several errors in the energy balance equation for the photoelectric effect are revealed. It is shown that the quantum yield influences Planck's constant. The need to account for the efficiency of photovoltaic energy converters (PVCs) and their relationship to quantum yield is substantiated. The true meaning of a radiation quantum as the energy required to maintain the "idle" state of a PVC is established, along with its dependence on the type of photocathode and its operating mode. Based on this, a classical explanation is given for the laws of the photoelectric effect discovered by A. Stoletov, and the conclusion is drawn that it is erroneous to contrast it with the laws of quantum mechanics.

Introduction

The question of the meaning of Planck's constant and its universality has expanded far beyond the realm of physics and acquired a deeper philosophical dimension. It reflects the general physical idea of the limited magnitude of "action" and the "continuity" of microprocesses in nature. "Planck's constant" is not only one of the calculated parameters of such processes, but also an expression of a new worldview based on calculations of the probability of a given event and requiring the selection of a specific "step" to reflect their discreteness, contrary to the classical physics notion of the continuous flow of time and the speed of real processes. This elevates the question of the magnitude of this step and the very possibility of "discretizing" space and time to the level of a philosophical one, despite its contradictory nature in the results of observations and experiments.

In this regard, understanding the meaning and physical validity of the very concept of a quantum, its origin, and its significance, is of no small importance. This is precisely what defines the physical and mathematical models that reflect the structure of matter and the laws governing the processes occurring within it. Differences in approaches and concepts on this issue give rise to endless debates about the nature of reality and the knowability of the material world.

The Origin of The Concept of Quantum

One of the main reasons that gave rise to the quantum-relativistic revolution at the turn of the 19th and 20th centuries was the lack of a satisfactory explanation for the experimentally established distribution of the spectral density of radiation of bodies [1]. By this time, it was already known that the radiation of bodies does not cease with the onset of thermal equilibrium, and the stationary state of the emitter is incompatible with equilibrium and is a consequence of the equality of the fluxes of radiated and absorbed energy. However, a theory of radiation that could take this circumstance into account did not exist at that time. Therefore, M. Planck, having received at the end of 1900 from F. Kurlbaum and G. Rubens the latest experimental data on the energy distribution in the spectrum of an absolutely black body (ABB), used L. Boltzmann's concept ofradiation as a type of ideal gases Witha certain temperature T And"electromagnetic" entropy S. Planck's focus at that time was the second derivative of the entropy of an ideal gas S with respect to its energy ∂2S/∂U2, which satisfied the aforementioned experimental data in the short-wavelength region (where Wien's law is valid), but was inversely proportional to the first power of the energy U in the long-wavelength region. Planck constructed their simplest generalization, a/U(U + b), and thereby found a "successful interpolation formula" satisfying the experimental data over the entire frequency range [2]. However, to justify this procedure, M. Planck had to resort to a number of postulates that contradicted classical physics.

Citation: Etkin V. The Quantum Of Radiation Or A Threshold Of Action?. Japan J Res. 2026;7(2):176.

The main one was the assumption that atoms of matter as oscillators can only be in certain discrete energy states with energies $\varepsilon_n = nh\nu$, multiples of the natural series of numbers n = 1, 2, ∞ and proportional to the frequency ν, emission and absorption of radiation occurs in indivisible portions (quanta) with energy $\varepsilon_\nu = h\nu$.In this case, the average statistical value of the oscillator energy‹εn› was discovered by M. Planck by approximating the sum of an infinite series of natural numbers n expression

$$\langle \varepsilon n\rangle = h\nu/[\exp(h\nu/kT) - 1]. \quad (1)$$

The product of this quantity by the spectral density of oscillators hν2/π2c3, found by Rayleigh (1900), allowed M. Planck to obtain the radiation law in the form.

$$u(\nu,T) = (8\pi h\nu^3/c^3)/[\exp(h\nu/) - 1], (J\,s\,m^{-3}). \quad (2)$$

This expression describes the radiation as a solid curve with a clearly defined maximum and a shape determined by a single parameter – the absolute temperature T. From Rayleigh's law

$$u(\nu,T) = (8\pi\nu^2/c^3)kT, \quad (3)$$

found six months earlier, it differs in that the value of kat is replaced by a more complex expression for the average energy ‹εn›. Although Planck's law described the experimental results perfectly, the very assumption of discreteness energy spectrum and the independence of the energy of a radiation quantum from the oscillation amplitude and the properties of the emitter and its temperature were in clear contradiction with the concepts of classical physics. Without going into the details of these contradictions, analyzed in a number of our works [3-6], we will only note that until the end of his life, M. Planck considered the problem of thermal radiation unsolved and did not abandon attempts in this direction [7].

The possibility of describing the radiation process without resorting to postulates alien to classical physics arose only with the transition to the thermodynamics of irreversible processes (TDI) [8, 9] and its generalization to processes of transfer and transformation of any forms of energy [10-12]. Below, we consider those of them that relate to the fundamental principles of quantum mechanics.

Non-postulate Derivation of Planck's Radiation Law

The fundamental distinction of the proposed approach from the perspective of energo- dynamics (ED) is the consideration of radiation as a process of radiant energy exchange between the emitter and its surrounding environment. This process is by no means reducible to heat exchange, which occupies a very small portion of the frequency range. In contrast, radiation is classified as an ordered form of energy exchange, accompanied by the performance of useful work "against equilibrium." This is evidenced by the phenomena of photosynthesis, photoelectric effects, photochemical, photonuclear, etc. The stationarity of the state of the emitter is determined in this case by the equality of the flows of absorbed and "re-radiated" energy, and not by their disappearance. This requires considering radiation not as a special substance, but as a process of converting the internal energy of the emitter U into a wave form of radiant energy carried by a light-bearing medium [3-6]. In this process, the frequency ν plays the role of the spectral flux of waves Jν= ν, i.e., the number of traveling single waves excited by the emitter in the environment per unit time. Thus, the frequency ν from the standpoint of ED acquires the meaning of a function of the radiation process, and not a function of the state of the emitter as a set of oscillators. It is quite natural that the flow of radiant energy in this case turns out to be proportional to the frequency as a function of the state of the emitter. This allows us to consider the emitter itself as an object of study. If we take into account that each of its atoms as an oscillator, in addition to the fundamental frequency of oscillation, νo has n harmonics corresponding to doubled, tripled, etc. frequency $\nu_n = n\nu_o$ (n = 1,2,3, etc.), then the oscillation energy of each such oscillator ε_n will appear as the sum of the energies ε_ν of all its n harmonics:

$$\varepsilon_n = \Sigma_n \varepsilon_\nu (J), \quad (4)$$

Formally, this expression differs from (1) $\varepsilon_n = n\varepsilon_o$ only in that in it the abstract numbers of the natural series n, which later gave the name to the whole of quantum mechanics (QM), are replaced by real harmonics inherent in any oscillator. However, in this case, the oscillator energy is no longer assumed to consist of n equal and indivisible parts (quanta) with the same energy $\varepsilon_o = h_\nu$, proportional to the frequency ν. This eliminates the need to average the oscillator energy εn over the number of oscillators oscillating at frequency ν, and allows us to find the statistically average value of the oscillator energy ‹εn› by expanding exp (–ε_ν/kT) in a series of n harmonics with subsequent approximation of this series by the expression

$$\langle\varepsilon_n\rangle = \varepsilon_\nu/[\exp(\varepsilon_\nu/kT) - 1]. \quad (5)$$

Now the density of the radiative energy flux $\rho_r = dj_r/dt$ is naturally determined by the product of the average value of the oscillator energy $\langle\varepsilon_n\rangle$ by the density of oscillators, determined by the expression $n\nu = 8\pi\nu^2/c^3$ found by Rayleigh:

$$\rho_r = \langle\varepsilon_n\rangle n_\nu, \quad (6)$$

Using (5), we arrive at the radiation law in the form:

$$\rho_r = (8\pi\nu^2\varepsilon\nu/c^3)/[\exp(\varepsilon_\nu/kT) - 1]\, J\,s\,m^{-3}. \quad (7)$$

To give the expression ε_ν/kT the form of the Kirchhoff function ν/kT, we multiply and divide ε_ν by the frequency ν as a value inverse to the duration of the oscillation τ, thereby giving the product of the energy of the oscillator oscillation mode εν by its duration $\varepsilon_\nu/\nu = \varepsilon_\nu\tau$ the meaning of an action, and we denote this action by h:

$$\varepsilon_\nu\tau \equiv h\,[J\,s]. \quad (8)$$

Substituting (8) into (7) directly leads to Planck's radiation law[2]:

$$\rho_\nu = (8\pi h\nu^3/c^3)/[\exp(h\nu/kT) - 1]. \quad (9)$$

However, now the quantum hypothesis no longer underlies it, since the value of h can be found from the Stefan-Boltzmann law $Jr = \sigma rT^4$ (W m^{-2}) for blackbodies (BB), as M. Planck did, or from experiments. Thus, Planck's radiation law in form (7) is valid for any emitter and can be obtained classically, without invoking the quantum hypothesis. This does not require postulating either the discreteness of the radiation process (which follows naturally from the finite duration of the oscillation) or the independence of the action from the oscillation amplitude and its frequency. However, the reason for the constancy of the value of h and the emergence of the concept of action, alien to classical thermodynamics, and its meaning remain unclear. To understand this, it is necessary to begin with the origin and meaning of this concept itself.

The Origin of The Concept of Action in Classical Physics

Although the concept of "action" plays a central role in traditional theoretical physics, it is mathematized, and its meaning remains unclear. Within the Lagrangian and Hamiltonian formalisms, the action S is a functional, i. e., a quantity that depends on the entire trajectory of the system's motion over time. According top principle of least action. Of all possible trajectories, the system selects the one on which the action is extreme (minimum, maximum, or stationary). However, for all its mathematical beauty and effectiveness, this definition of action does not provide a direct answer to the question: what is action as a physical quantity? Action remains an abstract, integral characteristic of motion.

Only in the works of ancient natural philosophers, and in particular Aristotle and his followers, do we find a direct connection between this concept and purposeful human activity and its results. In particular, G. Leibniz [8] mentioned the concept of action in connection with overcoming "dead forces" F, among which he included the compression forces of springs, gravitational, centrifugal forces, as well as the "quantity of motion" of R. Descartes [9] P = Mυ as the product of the amount of substance (mass M) of a generally motionless system such as the Universe and the speed υ of the internal vortex motion in it. Later, with the introduction of the concept of work (G. Cariolis, 1832) as the product of force F and the elementary displacement dr [11] caused by it and the advent of vector algebra, the concept of action began to acquire clearer outlines. It is the product of the impulse $P = M_υ$ (the former "quantity of motion" P = Mυ) and this displacement dr = υdt that is the quantity that is minimized in the principle of least action [12]:

$$M\upsilon \cdot dr = M\upsilon^2 dt = E\kappa dt, \text{J s}. \tag{4}$$

where $Ek = M\upsilon^2$ is Leibniz's "living force", understood as the internal kinetic energy of a system, i. e. the difference between its total and potential internal energy.

Thus, the quantity h, introduced by relation (8), is nothing more than the effect of a single oscillator oscillation on the surrounding light-bearing medium. However, this still does not reveal the reasons for this parameter's appearance in thermodynamics, the minimality of the quantum of action, its constancy, universality, etc.

To find out this r, let us consider an arbitrary system with a non-uniform distribution over its volume V of density $\rho_i = \rho_i(r, t)$ of some energy carriers Θi (mass M. number of moles of k-th substances Nk, charge Θe, entropy S, impulse J = Mυ, its momentum L, etc.), as shown in Fig. 1. As follows from the figure, when the distribution of Θi deviates from uniform (horizontal line), a certain amount of this quantity (marked in the figure by the star) is transferred from one part of the system to another, that you causes a shift in the center of this value from the initial position Ri0 to the current Ri. The position of these centers is determined by the well-known expression:

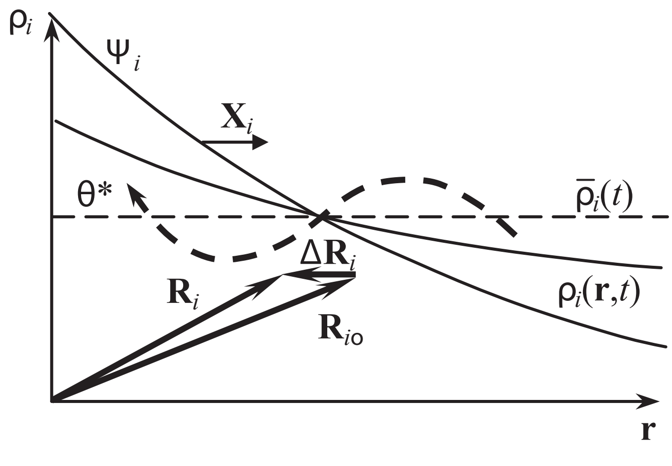

Figure 1. *On the concept of "action"*

$$R_i = \Theta^{-1}\int_v \rho_i(r,t) r dV; R_{i0} = \int_v \rho_{i0}(t) r dV = V^{-1}\int_v r dV \tag{5}$$

As follows from (5), in a spatially inhomogeneous system a certain "moment of distribution" Zi of energy carriers Θi arises [7].:

$$\boldsymbol{Z}_i = \Theta_i(\boldsymbol{R}_i - \boldsymbol{R}_{i0}) = \int_v [\rho_i(r,t) - \rho_{i0}(t)] r dV \tag{6}$$

where $\Delta R_i = R_i - R_i0$ – "displacement vector" as a specific action.

If we consider a certain non-deformable volume of space V filled with an arbitrary substance as the object of study, and combine R_i0 with the constant center of this volume by setting $R_i0 = 0$, then the distribution moment $Z_i = \Theta_i R_i$ will become a polar vector and an absolute measure of the deviation of the system as a whole from a homogeneous state.

A characteristic feature of the parameters Z_i is that they vanish as the system approaches internal equilibrium (a homogeneous state). These include, in particular, mechanical, thermal, electrical, magnetic, and other equilibria. This gives the concept of "action" the general physical meaning of "perturbation" as a process counteracting relaxation. The minimality of the work $W_i = \int F_i \cdot dR_i$ performed "against equilibrium" is the basis of the principle of least action. This also implies the universality of expressing the acting force Fi as the partial derivative of the system's internal energy U with respect to the corresponding action Ri:

$$F_i = (\partial U/\partial F_i = (\partial U/\partial R_i)\,\Theta_i. \tag{7}$$

This is where the concept of "action of force" comes from. Similarly, the partial derivative of the action Zi = ΘIrri with respect to time under the conditions Θi = const is the concept of the generalized impulse Ji:

$$J_i = dZ_i/dt = \Theta_i \upsilon_i. \tag{8}$$

With this approach, the action no longer appears as an abstract functional but becomes a state parameter capable of reflecting both the system's movement away from equilibrium ($dZ_i > 0$), and its approximation ($dZ_i < 0$) for any degree of freedom of the system.

In this case, the minimum value of h as a quantum of action and one of the parameters Z_i becomes a consequence of the principle of least action.

The Concept of "Action Threshold"

The third law of mechanics of I. Newton is formulated for the case when the externally applied (active) force Fa is opposed by the only reaction force of the system Fr:

$$F^a = -F^r. \tag{9}$$

However, this position is only valid for systems with a single degree of freedom. In the more general case of polyvariant systems with n degrees of freedom, any i -th active force $F_i > 0$ is opposed by n -1 reaction forces F_j:

$$F_i = -\Sigma_{n-1} F_j, \tag{10}$$

since in a closed system the sum of all internal forces ΣiFi =0 (i=1,2, n) is always equal to zero. This position underlies the thermodynamics of irreversible processes (TIP) [], according to the phenomenological laws of which each of the relaxation flows Ji generated by all forces present in the system Fj. The difference in their directions determines "branching" of a process along several trajectories, resulting in a resulting flow Ji may not match any of them. This generates a special kind of irreversibility, not directly related to the release of heat of dissipation. Such are, in particular, all processes associated with the transformation of the i-th form of energy into the j-th, where only one of the reaction forces F_j corresponds to the achievement of a useful effect. The power ratio $N_j = F_j \cdot \upsilon_j$ and $N_i = F_i \cdot \upsilon_i$ of these processes, expressing the actions of forces F_j and F_i per unit of time, and defines the concept of the efficiency coefficient (efficiency) of this process ηij:

$$\eta_{ij} = N_j/N_i = F_j \cdot \upsilon_j / F_i \cdot \upsilon_i. \quad (11)$$

Obviously, this efficiency is less than unity, since F_j is only one of the forces opposing F_i. The difference F_i - F_j between the applied force and the useful reaction force Fj is obviously equal to the sum of n - 1 "side" reaction forces, which determines the so-called "action threshold" of the active force. This makes the concept of "action threshold» a general, fundamental concept. In specific physical and technical systems, it manifests itself through a multitude of particular, measurable threshold values. In particular, this is the "operation threshold" of various mechanisms, the "sensitivity threshold" of measuring instruments, the "threshold of chemical and nuclear reactions," the "destruction threshold" of materials, the "threshold stimulus" for a qualitative leap in the evolution of biosystems, etc. The existence of an "action threshold" is also demonstrated by classical physics. Such are static friction, electrical breakdown in insulators and semiconductors, the detonation of explosives, etc. These examples demonstrate that the action threshold is n ot an abstraction, but a fundamental, universally observable property of the material world.

The True Meaning of A Quantum of Radiation

Introducing the proportionality coefficient Between the frequency ν and the quantum energy εν, M. Planck postulated its independence from the nature of the oscillator and its state. This gave A. Einstein grounds to assert in his famous 1905 article [2] the universality of Planck's constant for any radiating bodies and processes in the microworld.

To confirm this thesis, he recorded the energy balance in the photoelectric effect through the energy of a radiation quantum hνin the form of a ratio:

$$= (We + Ek), \quad (12\text{- }4)$$

where hν is the energy of a hypothetical particle, later called a photon; W_e, E_k is the work function of the photoelectron (ionization energy of the atom) and its kinetic energy.

According to this expression, the photoelectric effect does not occur if the photon energy h $\nu < W_e$, i.e., it is insufficient to ionize the atom (perform the work function W_e). In this case, this energy is minimal if the emitted electron does not have kinetic energy (Ek = 0) and increases linearly with increasing frequency ν of the absorbed photons.

This explanation of the photoelectric effect gave the magnitude hν the meaning of the minimum energy of absorbed radiation sufficient for the emission of a photoelectron by any photocathode without its further acceleration (Ek = 0). It looked so convincing that A. Einstein's contemporaries and the Nobel Committee did not pay attention to its inconsistency.

Indeed, it followed from it that before the onset of photoemission (*We+ Ek= 0*) the energy balance in (12) is not observed. This is equivalent to violating the law of conservation of energy, of which it is a special case. Secondly, in (12) the dimensionality rule is violated, its left-hand side refers to the photon (J/photon), and the right-hand side – to the electron (J/electron). This means that it lacks a factor characterizing the ratio of the number of emitted electrons to the number of absorbed photons. This quantity is known as the "quantum yield" $S_\lambda = J_e/J_v$ and is defined as the ratio of the photocurrent Ie = qe Je (A) to the radiant flux J_v (W). It varies over a very wide range (from ~10 -4 to 2), which makes it necessary to take it into account [4]. Thirdly, relation (4) does not take into account the efficiency of the process of converting radiant energy into electrical energy, which is mandatory for any real energy converters. Fourthly, this relation is valid only for the special case of "single-photon" photoemission. Meanwhile, A. Einstein himself noted that already at a wavelength of 0.5 μm and T = 1700 K, the quantum energy is 6.5 107 times greater than the energy of the oscillator itself, found from the value of its energy [2]. Fifthly, relation (12) does not contain the concept of luminous flux Jν (W) and therefore does not reflect the possible dependence of the kinetic energy of photoelectrons on it. Ek at a constant photocurrent (Stoletov's first law [5]).

However, even more importantly, this ratio does not take into account the spectral sensitivity of photocathodes, which is manifested in the dependence of their efficiency (photocurrent Ie) on the frequency ν), since according to (12) at Ek = 0 the derivative (∂We/∂ν) Ek = h is constant for all photocathodes in the entire frequency range. Considering the quantum yield Sλ, even in the absence of side photoeffects (photoluminescence, photochemical, photonuclear transformations, photosynthesis, etc.), relation (12) takes the form:

$$S\lambda h\nu = (We + Ek). \quad (13)$$

It is easy to see that in this case, the derivative (∂We/∂ν) is not equal to h even in the absence of all other types of work except electron emission. Nevertheless, to date, Einstein's relation (12) has been used to experimentally determine the constant h, and the influence of the cable-stayed output Sλ on the value of Planck's constant has been denied. This is based on the results of experiments measuring it using the same expression (12).

To understand the inconsistency of such a link, let us consider the method of these experiments. They use a vacuum photovoltaic energy converter (PVC), consisting of an anode and a cathode, between which the voltage Δφ can be varied. The cathode is illuminated with monochromatic light, for which various light filters or monochromators are used. By varying the "cut-off voltage" Δφ at the PVC output, its value Δφo is fixed, at which the photocurrent Ie practically ceases. By alternately changing the illumination of the photocathode with waves of different lengths and measuring the value of Δφo for each fixed wavelength, a graph of its dependence on frequency is plotted, and from the tangent of its slope (∂Δφo/∂ν) we obtain Planck's constant h.

Thus, in each such experiment, a threshold value is decided h and Δφo, corresponding to the "idle run" of the solar cell, when Sλ=0 and therefore cannot influence experimental results. This led to the conclusion about the universality of the quantum of action.

In all the above-mentioned contradictions disappear if the balance equation for a solar cell and any other energy converter is written using the concept of its efficiency ηϕin accordance with expression (11):

$$J\nu\, \eta\phi = Ie\, \Delta\varphi. \quad (14)$$

In this expression Jν =Jϕεν and Ie= qeJe,, so that ηϕ = qeJeΔφ/Jϕεν is related to the quantum yield of the photocathode Sλ =Je/Jν by a simple relation

$$\eta\phi = S\lambda\Delta\varphi. \quad (15)$$

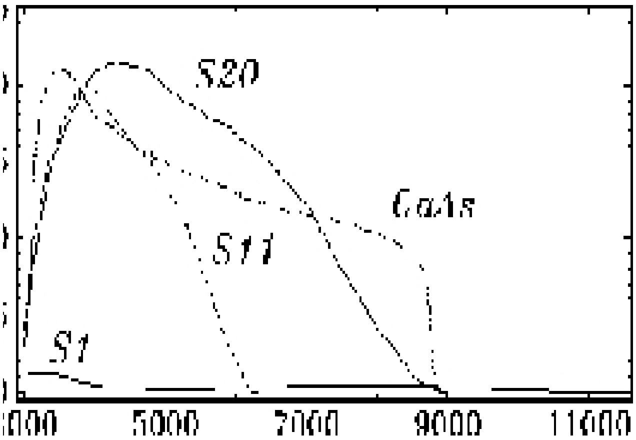

Figure 2. *Spectral characteristics of a number of photocathodes (DataSheet.ru)*

It follows that considering the quantum yield of the photocathode Sλ or the efficiency ηφ in relation (12) is mandatory. This also follows from the similar theory of any (thermal and non-thermal, cyclic, non-cyclic, direct, and inverse) machines, which was developed within the framework of energy dynamics [11]. According to it, the power efficiency ηij of any energy converter has a maximum at a certain load of the installation (in this case, the frequency ν) and turns to zero twice: at "idle", when ,Je=0 , and in the "short-circuit" mode, when Δφ =0. This is confirmed by the characteristics of the quantum yield of any photocathodes, including those shown in Figure 1. Where the relative quantum yield Sλ(%) of a number of photocathodes is given as a function of the wavelength (nm) of the incident monochromatic radiation.

In general, Sλ depends not only on the wavelength and properties of the photocathode, but also on its structure, surface treatment method, coating, temperature, and operating conditions, and for most photocathodes, it does not exceed 0.001. Clearly, the lower ηф and Sλ, the greater the energy required for the photoemission of a single electron, according to (14). This refutes the assumption of the "universality" of the quantum of study for all photocathodes, and especially for all processes of converting radiant energy into other forms.

This conclusion is also confirmed for FEP. According to (14), ηф vanishes twice: in the "idle mode" of the photoelectric converter, when Je = 0, and in the "short circuit" mode, when Δφ = 0. The idle mode, realized in experiments to study photoemission, characterizes the "threshold action" discussed above, i.e. That minimum power Nj =ενvο, which must be supplied to the solar cell to begin the emission of photoelectrons. If the emfΔφwas the only opposing force, and "threshold action" was absent, then there would also be the "red limit" of the photoelectric effect. Consequently, it should depend on the individual properties of the photocathodes, varying widely along with the quantum yield, without directly relating to the concept of a radiation quantum as its "minimum portion," absorbed or emitted entirely. Therefore, in experiments based on Einstein's relation (12), what is actually measured is not the radiation quantum, but the "action threshold," i.e., the "idle-running" losses of the solar cell. These losses are inherent in all energy converters without exception and have no relation to the quantum (discrete) nature of the radiation process.

Conclusion

Within the framework of the proposed approach, free of any quantum-mechanical postulates, the absence of an insurmountable contradiction between classical and quantum mechanics becomes apparent. It becomes clear that the concept of an action threshold is not just another term in the physics lexicon, but a key element of a methodology that seeks to return physics to the path blazed by classical science—a path from observation and experiment to generalization and understanding of the deep mechanisms of the universe. Based on the above, it can be argued that the use of phenomenological, observable, and measurable concepts such as "action" and "action threshold" opens the way to constructing a physical reality based on experience and cause-and-effect relationships. Instead of postulating "freely invented" postulates (for example, energy quantization), the proposed approach allows for the study of observable threshold phenomena and the derivation of general patterns from them. This allows for the creation of a more holistic, logically consistent, and, importantly, intuitive picture of the world.

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