A Continuous-Field Interpretation of the Photoelectric Effect

The Roles of Magnetic-Field Dynamics, Force, Impulse, and Interaction Geometry

Franc Rozman & UI

Abstract

The photoelectric effect is commonly interpreted as the absorption of discrete photons whose energy is proportional to frequency. This paper explores an alternative description in which electron ejection is treated as a dynamical interaction between a continuous electromagnetic wave and a bound electron. The proposed model is based on four physical quantities: the temporal variation of the magnetic field, the effective force acting on the electron, the impulse transferred during the interaction, and the geometrical configuration of the encounter.

Assuming, as a working hypothesis, that elementary electromagnetic-wave structures possess approximately the same maximum magnetic-field amplitude, the maximum rate of magnetic-field variation increases linearly with frequency. Within this framework, electron emission is proposed to require not only that the instantaneous force exceed a critical value but also that the transferred impulse be sufficient to overcome the electron binding.

The interaction is further assumed to depend on the relative geometry between the electromagnetic wave and the bound electron. This geometrical factor provides a possible physical interpretation of the photoionization cross section and of its experimentally observed decrease with increasing photon energy above the ionization threshold.

The paper develops this continuous-field force–impulse–geometry model, applies it qualitatively to the photoionization of ground-state hydrogen, and proposes a phenomenological continuous-field interpretation of the principal experimental characteristics of the photoelectric effect.

1. Introduction

Since its discovery at the beginning of the twentieth century, the photoelectric effect has played a central role in the development of modern physics. Experimental observations demonstrated that electrons are emitted from a material only when the frequency of the incident electromagnetic radiation exceeds a characteristic threshold. The kinetic energy of the emitted electrons was found to increase with the frequency of the radiation, while the intensity primarily affects the number of emitted electrons. These observations led to Einstein's interpretation of light as consisting of discrete energy quanta, later called photons, an explanation that became one of the foundations of quantum mechanics.

Although the quantum description successfully predicts the measurable characteristics of the photoelectric effect, the physical mechanism by which electromagnetic radiation transfers energy and momentum to a bound electron remains a subject of interpretation. In particular, the process is usually described in terms of photon absorption, while the detailed dynamical interaction between the electromagnetic field and the electron is not explicitly represented in classical field quantities such as electric and magnetic field strengths or their temporal evolution.

The present work explores an alternative interpretation based on the dynamics of a continuous electromagnetic wave. Rather than introducing localized photons as the primary physical entities, the proposed model considers the interaction between a continuous electromagnetic-wave structure and a bound electron. Particular attention is given to the dynamical evolution of the electromagnetic field, the effective force acting on the electron, the impulse transferred during the interaction, and the relative geometry of the encounter between the wave and the electron.

Within this framework, electron ejection is proposed to require the simultaneous fulfilment of two physical conditions. First, the instantaneous effective force exerted by the electromagnetic field must exceed a critical value determined by the electron's binding. Second, the interaction must transfer a sufficient impulse to allow the electron to escape from the bound state. In addition, the efficiency of the interaction is assumed to depend on the relative orientation between the electromagnetic wave and the electron, providing a possible physical interpretation of the experimentally observed photoionization cross sections.

The objective of this paper is not to replace the successful quantitative predictions of quantum theory, but to investigate whether the photoelectric effect can also be described as a continuous-field interaction governed by electromagnetic-field dynamics, force, impulse, and interaction geometry. The proposed model is then compared qualitatively with established experimental observations, with particular emphasis on the photoionization of atomic hydrogen, the simplest atomic system for which extensive experimental data are available.

2. Experimental Characteristics of the Photoelectric Effect

The photoelectric effect has been investigated extensively for more than a century and is among the best-characterized phenomena in atomic physics. Independent of its theoretical interpretation, several experimental features are consistently observed and provide the foundation for any physical model of electron emission.

The first fundamental observation is the existence of a threshold frequency. Electrons are emitted only when the frequency of the incident electromagnetic radiation exceeds a characteristic value determined by the binding energy of the electron in the material. Radiation of greater intensity but lower frequency does not produce photoelectron emission, regardless of the duration of illumination.

The second fundamental observation concerns the energy of the emitted electrons. Once the threshold frequency is exceeded, the maximum kinetic energy of the photoelectrons increases with the frequency of the incident electromagnetic radiation. Increasing the intensity of the radiation, while keeping its frequency unchanged, does not increase the maximum kinetic energy of the emitted electrons. Instead, it primarily increases the number of emitted electrons. Thus, the energy of individual photoelectrons is determined mainly by the frequency of the incident radiation, whereas the intensity governs the emission rate.

A third important experimental observation is that electron emission remains probabilistic even when the incident radiation exceeds the ionization threshold. Not every interaction between an electromagnetic wave and a bound electron results in electron ejection.

Instead, the probability of ionization depends on the energy of the incident radiation and is quantified by the photoionization cross section, a measure of the likelihood that an incident electromagnetic wave will eject a bound electron.

For the hydrogen atom, the simplest atomic system, the photoionization cross section reaches its maximum close to the ionization threshold and decreases steadily as the photon energy increases. Many multi-electron atoms exhibit the same general trend, although additional resonances may appear because of their more complex electronic structure. The measured values of the photoionization cross section are independent of theoretical interpretation and therefore provide an important experimental constraint for any physical model of the photoelectric effect.

For the hydrogen atom, the ionization threshold corresponds to a binding energy of 13.6 eV. Representative values of the photoionization cross section are summarized in Table 1.

Photon energy (eV)	Wavelength (nm)	Relative photoionization cross section
13.6	91.2	1.000
20	62.0	0.348
30	41.3	0.111
50	24.8	0.025
100	12.4	0.003

Table 1. Representative photoionization cross sections for ground-state hydrogen.

These experimental observations establish three principal facts that any physical description of the photoelectric effect must explain:

1. the existence of a threshold frequency,
2. the dependence of photoelectron energy on radiation frequency rather than intensity,
3. the systematic variation of the photoionization cross section with photon energy.

The following sections develop a continuous-field interpretation that seeks to explain these experimental observations in terms of electromagnetic-field dynamics, force, impulse, and interaction geometry rather than localized energy-transfer events.

3. Electromagnetic Wave as a Continuous Physical Structure

The present work considers an electromagnetic wave as a continuous physical structure extending through space and evolving continuously in time. Within this description, the interaction between electromagnetic radiation and a bound electron is not regarded as an instantaneous transfer of energy but as a dynamical process that develops throughout the encounter between the electromagnetic field and the electron.

The electromagnetic wave is characterized by continuously varying electric and magnetic fields. At any point in space, these fields change smoothly with time, and the interaction with the electron is therefore also continuous. In the present model, particular attention is given to the temporal behaviour of the magnetic field, since its rate of change is proposed to play an important role in determining the effectiveness of electron ejection.

For a monochromatic electromagnetic wave, the magnetic field at a fixed point in space may be written as

$$B(t) = B_0 \sin(2\pi f t + \varphi),$$

where B_0 is the maximum magnetic-field amplitude, f is the wave frequency, and ϕ is the phase.

Differentiating with respect to time gives the temporal variation of the magnetic field,

$$\frac{dB}{dt} = 2\pi f B_0 \cos(2\pi f t + \varphi),$$

whose maximum absolute value is

$$\left|\frac{dB}{dt}\right|_{\max} = 2\pi f B_0.$$

These relations are direct mathematical consequences of the harmonic form of the electromagnetic wave. They show that the maximum rate of magnetic-field variation depends on both the wave frequency and the magnetic-field amplitude.

The present model introduces the working hypothesis that elementary electromagnetic-wave structures possess approximately the same characteristic maximum magnetic-field amplitude, independent of their frequency,

$$B_0 \approx \text{constant}.$$

Under this assumption,

$$\left|\frac{dB}{dt}\right|_{\max} \propto f.$$

Higher-frequency electromagnetic waves would therefore produce more rapid temporal variations of the magnetic field than lower-frequency waves. The following section examines how this rapidly varying electromagnetic field may generate the force required for electron ejection.

4. Time Variation of the Magnetic Field

The magnetic component of a monochromatic electromagnetic wave varies continuously in space and time. For a plane wave propagating in the x-direction, it may be represented as

$$B(x,t) = B_0 \sin(kx - \omega t + \varphi)\,, \tag{1}$$

where B_0 is the maximum magnetic-field amplitude, k is the wave number, ω is the angular frequency, and ϕ is the phase constant. The wave number and angular frequency are related to the wavelength λ and ordinary frequency by

$$k = \frac{2\pi}{\lambda}, \qquad \omega = 2\pi f. \tag{2}$$

At a fixed position $x=x_0$, the spatial part of the phase is constant, and the magnetic field can therefore be written in the simpler form

$$B(t) = B_0 \sin(\omega t + \varphi_0)\,, \tag{3}$$

where ϕ_0 incorporates the fixed spatial phase. Differentiation with respect to time gives

$$\frac{dB}{dt} = \omega B_0 \cos(\omega t + \varphi_0)\,. \tag{4}$$

The maximum magnitude of the temporal variation is consequently

$$\left|\frac{dB}{dt}\right|_{\max} = \omega B_0 = 2\pi f B_0. \tag{5}$$

Equation (5) is a direct consequence of the harmonic representation of the electromagnetic wave. It shows that the maximum rate of magnetic-field variation depends on two quantities: the frequency f and the magnetic-field amplitude B_0. Frequency alone therefore does not determine the value of $|dB/dt|_{\max}$.

The present model introduces the following working hypothesis:

$$B_0 \approx \text{constant} \tag{6}$$

for elementary electromagnetic-wave structures associated with different frequencies. This assumption is not derived from classical electrodynamics and should not be interpreted as a general property of macroscopic electromagnetic waves. It is introduced as a phenomenological hypothesis whose consequences for electron ejection are examined in the following sections.

Under this assumption, Equation (5) becomes

$$\left|\frac{dB}{dt}\right|_{\max} \propto f. \tag{7}$$

Thus, an increase in frequency produces a proportionally larger maximum rate of magnetic-field variation. A higher-frequency wave passes through the same sequence of field values in a shorter time and therefore produces a more rapid local change of the magnetic field.

The characteristic duration of one half-cycle is

$$\Delta t_{\frac{1}{2}} = \frac{T}{2} = \frac{1}{2f}, \tag{8}$$

where T=1/f is the oscillation period. Increasing the frequency therefore has two simultaneous consequences:

$$\left|\frac{dB}{dt}\right|_{\max} \propto f, \qquad \Delta t_{\frac{1}{2}} \propto \frac{1}{f}. \tag{9}$$

The first relation indicates increasingly rapid field variation, whereas the second indicates a progressively shorter interval during which the field acts in a particular direction. These opposing frequency dependences form the central dynamical feature of the proposed model. They allow the effective force to increase with frequency while the duration available for transferring mechanical impulse decreases.

In the present interpretation, the temporal variation of the magnetic field is therefore not itself identified with the mechanical force acting on the electron. Rather, it is treated as the field-dynamical quantity from which the effective interaction force is assumed to arise.

The next section introduces this effective force and examines the impulse transferred to the bound electron during the interaction.

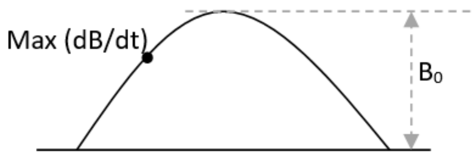

Figure 1. *Working hypothesis of the present model. If elementary electromagnetic-wave structures possess approximately the same maximum magnetic-field amplitude B_0, the maximum rate of magnetic-field variation increases proportionally with frequency.*

5. Force and Impulse During Electron Ejection

The previous section showed that, under the working hypothesis of approximately constant magnetic-field amplitude, the maximum rate of magnetic-field variation increases proportionally with frequency. The present model assumes that this rapidly varying electromagnetic field gives rise to an effective interaction force acting on the bound electron.

The precise microscopic origin of this effective force is not specified within the present phenomenological model. Instead, it is assumed that the magnitude of the force increases monotonically with the rate of magnetic-field variation. Symbolically,

$$F_{\text{eff}} \propto \left|\frac{dB}{dt}\right|. \tag{10}$$

Since

$$\left|\frac{dB}{dt}\right|_{\max} \propto f, \tag{11}$$

the maximum effective force is likewise expected to increase approximately in proportion to the wave frequency,

$$F_{\max} \propto f. \tag{12}$$

Electron emission is proposed to occur only if the effective force exceeds a critical value determined by the binding of the electron,

$$F_{\max} \geq F_{\text{crit}}. \tag{13}$$

This condition explains naturally why electromagnetic radiation below a certain frequency is unable to produce electron emission. Although the electromagnetic field acts on the bound electron, the maximum effective force never reaches the level required to overcome the binding interaction.

The magnitude of the force alone, however, is not sufficient to determine whether the electron escapes. A sufficiently large force acting for an extremely short time may still transfer too little mechanical momentum to release the electron from the atom.

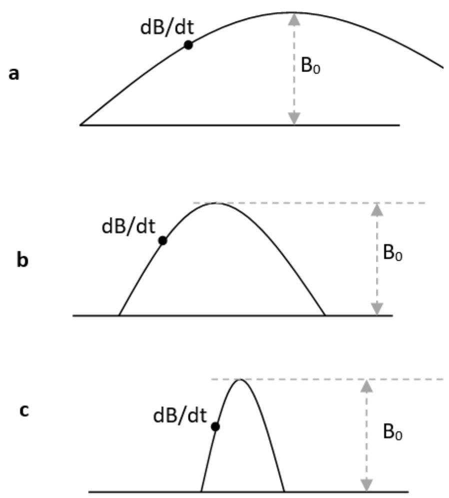

Figure 2. *Schematic comparison of electromagnetic waves with increasing frequency. Assuming the same maximum magnetic-field amplitude B_0, higher frequencies produce larger values of $|dB/dt|_{max}$, while the duration of each half-cycle decreases in inverse proportion to frequency.*

The relevant mechanical quantity is therefore the impulse,

$$J = \int F_{\text{eff}}(t)\, dt, \tag{14}$$

which represents the total momentum transferred during the interaction.

Because the characteristic duration of one half-cycle decreases with increasing frequency,

$$\Delta t \propto \frac{1}{f}, \tag{15}$$

the impulse depends on two competing effects. Increasing frequency increases the maximum force while simultaneously reducing the interaction time.

Expressed schematically,

$$J \sim F_{\max}\, \Delta t. \tag{16}$$

Since

$$F_{\max} \propto f, \qquad \Delta t \propto \frac{1}{f}, \tag{17}$$

the impulse is not expected to increase indefinitely with frequency. Instead, it is anticipated to reach a maximum and subsequently decrease as the interaction interval becomes progressively shorter.

Electron emission is therefore proposed to require a second independent condition,

$$J \geq J_{\text{crit}}, \tag{18}$$

where J_{crit} denotes the minimum impulse necessary for the electron to escape from its bound state.

Within the present model, successful photoelectron emission occurs only when **both** physical requirements are simultaneously satisfied:

$$F_{\max} \geq F_{\text{crit}} \quad \text{and} \quad J \geq J_{\text{crit}}. \tag{19}$$

These two conditions provide the physical basis for the interpretation developed in the following sections. The force criterion explains the existence of the photoelectric threshold, whereas the impulse criterion provides a natural mechanism for the decrease of the photoionization cross section at higher photon energies.

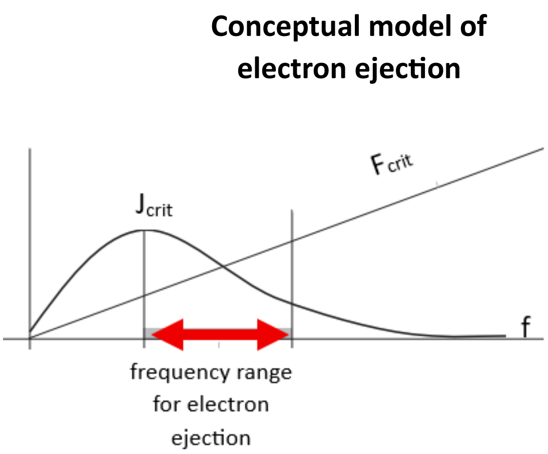

Figure 3 *Qualitative interpretation of the photoionization threshold. The effective force increases with frequency, whereas the transferred impulse reaches a maximum and subsequently decreases because of the shortening interaction time. Electron emission is expected only within the frequency interval where both the force and impulse exceed their critical values.*

6. Geometrical Conditions of Interaction

The force and impulse criteria introduced in the previous section are proposed as necessary conditions for electron emission. They are, however, not considered sufficient by themselves. Even when both quantities exceed their respective critical values, the interaction between an electromagnetic wave and a bound electron is expected to depend on their relative geometry.

An electromagnetic wave possesses a well-defined propagation direction together with mutually perpendicular electric and magnetic fields. Likewise, a bound electron occupies a spatially distributed electronic state whose local orientation relative to the incident wave may vary from one interaction to another. Consequently, the effectiveness of the interaction is expected to depend not only on the magnitude of the electromagnetic field but also on the relative orientation between the wave and the electron.

The present model therefore introduces a geometrical factor,

$$G(\theta), \tag{20}$$

where θ denotes an appropriate angle describing the relative orientation between the incident electromagnetic wave and the effective direction of the electron interaction. The precise functional form of G(θ) is not specified in the present work and may depend on the detailed microscopic description of the interaction.

The geometrical factor is assumed to satisfy

$$0 \leq G(\theta) \leq 1, \tag{21}$$

where values close to unity correspond to favourable interaction geometries, whereas values approaching zero represent geometries in which electron ejection is unlikely despite otherwise favourable force and impulse conditions.

The effective interaction responsible for electron emission may therefore be expressed schematically as

$$P_{\text{eff}} \propto F_{\text{eff}}\, J\, G(\theta), \tag{22}$$

where P_{eff} represents a qualitative measure of the effectiveness of the interaction rather than a normalized probability.

Within this interpretation, successful photoelectron emission requires the simultaneous fulfilment of three independent conditions:

$$F_{\max} \geq F_{\text{crit}}, \tag{23}$$

$$J \geq J_{\text{crit}}, \tag{24}$$

and

$$G(\theta) > 0. \tag{25}$$

Only interactions satisfying all three conditions are expected to produce electron emission. Consequently, even electromagnetic radiation with sufficient frequency does not necessarily ionize every atom that it encounters.

The geometrical factor provides a natural interpretation of why the photoelectric effect remains probabilistic on the microscopic scale despite the deterministic evolution of the electromagnetic field. Different encounters between electromagnetic waves and bound electrons generally occur with different relative orientations and therefore possess different probabilities of satisfying the complete set of emission conditions.

In the following section, this geometrical interpretation is compared qualitatively with experimentally measured photoionization cross sections.

7. Interpretation of Photoionization Cross Sections

One of the most characteristic experimental features of photoionization is the systematic variation of the photoionization cross section with photon energy. For hydrogen, the cross section reaches its maximum close to the ionization threshold and decreases steadily as the photon energy increases. Similar trends are observed for many other atoms, although additional resonances may appear because of their more complex electronic structures.

Within the present model, this behaviour follows naturally from the combined influence of the force, impulse, and geometrical conditions introduced in the preceding sections.

Near the ionization threshold, the effective force is only slightly above the critical value required for electron emission. At the same time, however, the interaction interval remains relatively long, allowing a substantial mechanical impulse to be transferred to the electron. These conditions favour successful electron emission whenever the geometrical orientation is also favourable.

As the radiation frequency increases, the effective force continues to increase because of the increasingly rapid temporal variation of the magnetic field. Simultaneously, however, the interaction interval becomes progressively shorter. Although the instantaneous force becomes larger, the shorter duration reduces the efficiency with which mechanical impulse can be transferred.

Consequently, the probability that all three conditions—

$$F_{\max} \geq F_{\text{crit}},$$
$$J \geq J_{\text{crit}},$$

and

$$G(\theta) > 0,$$

are simultaneously satisfied decreases with increasing photon energy.

The measured photoionization cross section may therefore be interpreted as the fraction of all encounters between electromagnetic waves and bound electrons that satisfy the complete set of emission conditions. Symbolically,

$$\sigma \propto \Phi(F, J, G), \tag{26}$$

where Φ denotes an unknown function describing the combined influence of force, impulse, and interaction geometry. The present work does not attempt to determine the explicit analytical form of this function. Instead, it proposes that the experimentally observed behaviour of the photoionization cross section reflects the simultaneous action of these three physical factors.

This interpretation reproduces the principal qualitative features of the measured hydrogen photoionization cross section. The existence of a threshold follows from the critical-force condition, while the subsequent decrease of the cross section is associated with the progressive reduction of the effective impulse transfer and the geometrical constraints on successful interaction.

The proposed interpretation is intended as a phenomenological description rather than a replacement for quantum-mechanical calculations. Its purpose is to provide an alternative physical picture that relates the observed photoionization probability to the dynamics of continuous electromagnetic fields.

An important consequence of the proposed interpretation is that the photoionization cross section is viewed as a statistical property emerging from many individual wave–electron encounters rather than as an intrinsic property of isolated photons. In this picture, the measured cross section reflects the fraction of interactions in which the combined requirements of force, impulse, and favourable geometry are simultaneously fulfilled.

8. Discussion and Limitations

The model presented in this work provides a continuous-field interpretation of the photoelectric effect based on three physical ingredients: the effective interaction force, the transferred impulse, and the geometrical conditions of interaction between the electromagnetic wave and the bound electron.

Within this framework, several well-established experimental observations receive a simple qualitative interpretation. The existence of a threshold frequency follows naturally from the requirement that the effective force must exceed a critical value. The subsequent decrease of the photoionization cross section is interpreted as the consequence of progressively shorter interaction times that reduce the transferred impulse despite increasing instantaneous force. The probabilistic nature of photoelectron emission is attributed to variations in the relative geometry of individual wave–electron encounters.

The present model is intentionally phenomenological. It does not attempt to replace the quantitative predictions of quantum electrodynamics, nor does it derive the microscopic interaction from first principles. Instead, it proposes an alternative physical picture that relates the observed behaviour of the photoelectric effect to the dynamics of continuous electromagnetic fields.

Several assumptions introduced in the model require further investigation. In particular, the hypothesis that elementary electromagnetic-wave structures possess approximately the same characteristic maximum magnetic-field amplitude has been adopted as a working assumption rather than derived from established electromagnetic theory. Likewise, the explicit functional dependence of the effective force on the magnetic-field dynamics and the analytical form of the combined function describing the photoionization cross section remain to be established.

The proposed interpretation nevertheless suggests several directions for future theoretical and experimental work. Numerical modelling of the interaction between continuous electromagnetic fields and bound electrons may help determine the functional dependence of the effective force and impulse. Experimental studies comparing photoionization cross sections over broad energy ranges may further test whether the proposed qualitative trends are consistent with observation.

The principal contribution of the present work is therefore not the introduction of new experimental facts, but the proposal of an alternative conceptual framework in which the photoelectric effect is interpreted as the result of continuous electromagnetic-field dynamics rather than instantaneous localized energy-transfer events.

The novelty of the proposed interpretation lies not in modifying the experimentally established characteristics of the photoelectric effect, but in providing a different physical organization of these observations. The threshold frequency, the variation of the photoionization cross section, and the probabilistic character of electron emission are interpreted as different manifestations of the same underlying interaction involving force, impulse, and geometrical conditions.

9. Conclusions

This work has presented a continuous-field interpretation of the photoelectric effect based on the dynamics of electromagnetic fields rather than on instantaneous localized energy-transfer events.

The proposed phenomenological model introduces three complementary physical ingredients governing electron emission:

- an effective interaction force associated with the temporal variation of the magnetic field,
- the mechanical impulse transferred during the interaction,
- the geometrical conditions between the electromagnetic wave and the bound electron.

Within this framework, the threshold frequency is interpreted as the consequence of a critical-force condition, whereas the subsequent decrease of the photoionization cross section is attributed to the combined effects of diminishing impulse transfer and interaction geometry as the frequency increases.

The model does not attempt to replace the quantitative formalism of quantum mechanics. Instead, it provides an alternative physical picture in which experimentally observed photoionization probabilities emerge from the combined action of force, impulse, and geometrical conditions during continuous wave–electron interactions.

The proposed interpretation remains phenomenological and introduces several working assumptions whose microscopic origin has not yet been established. Nevertheless, it offers a unified conceptual framework capable of relating several independent experimental characteristics of the photoelectric effect through a common physical mechanism.

Further theoretical development and experimental investigation will be required to determine the quantitative form of the proposed interaction and to evaluate its relationship to established quantum descriptions. The present work is intended as a contribution toward such investigations by providing a physically transparent interpretation of the interaction between continuous electromagnetic fields and bound electrons.

More generally, the present work illustrates that continuous electromagnetic-field models may provide additional physical insight into processes that are commonly described solely in terms of photon absorption. Whether this interpretation can be extended to other light–matter interactions remains an open question for future research.