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Unipolar pulse of an electromagnetic field with uniform motion of a charge in a vacuum

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Contents

Abstract. Progress in the generation of extremely short pulses of electromagnetic radiation makes the question of the properties of the limiting form of their shortening — unipolar pulses with a significant zero-frequency component of the spectrum, that is, the electric area of the pulse — relevant. Recently, it has been established that it is the electric area that determines the effectiveness of the impact of extremely short pulses on micro-objects. At the same time, unipolar pulses have a number of unusual properties, which makes some researchers doubt the possibility of their existence and propagation. Here, we show that a uniformly moving relativistic electric charge creates a short unipolar pulse of the electromagnetic field. Unipolarity is realized as well for transition radiation. We also present the unipolarity condition for a pair of charges — a dipole — and for a more general system of moving charges. This confirms the reality of unipolar electromagnetic pulses, which are promising for applications of extremely short pulses.

Keywords: unipolar electromagnetic pulses, pulse electric area, field of moving electric charges

1. Introduction

One important trend in modern laser physics and nonlinear optics is the generation of ever shorter radiation pulses, with durations currently reaching the attosecond range [1–4]. The achievement of such durations promises revolutionary changes in laser technology and also offers unique opportunities for research in physics, chemistry, biology, and other disciplines.

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The limiting stage of pulse shortening when maximum frequencies are fixed is the generation of unipolar pulses whose spectrum contains a substantial zero frequency component. Due to the short duration of such 'delta'-like pulses, their exact shape is irrelevant, and they are characterized by their electric area

$$\mathbf{S}_E = \int \mathbf{E}\, \mathrm{d}t\,, \tag{1}$$

where $\mathbf{E}(\mathbf{r}, t)$ is the electric field, $\mathbf{r}$ is the radius vector, and t is time. It has already been shown that namely the electric area of extremely short pulses defines the efficiency of their action on electrons in bound states in atoms, molecules, and quantum points [5–13], as well as on free electrons [14], in particular on their spin [15, 16] (see also reviews [17, 18]). The efficiency is related to the unidirectional action of such pulses on charges, while for bipolar multi-cycle pulses this direction changes to the opposite one for each half of the oscillation cycle. For free electrons, the efficiency is maintained if the pulse duration is short enough such that for this time the electron stays in the region where the field is homogeneous [14]. In the case of atoms, the pulse duration should be less than the Keplerian period of electron rotation in the Bohr orbit. In this case, the action is reduced to a momentary 'kick,' as a result of which an electron with charge e acquires an additional mechanical momentum $e\mathbf{S}_E$. Such a scenario is described by the theory of sudden perturbations [19–23].

For these reasons, unipolar or quasi-unipolar radiation pulses with a substantial electric area are promising for improving the efficiency of the action on objects. However, the physics of such pulses differs considerably from the traditional physics, which developed mainly for multi-cycle pulses and quasi-monochromatic radiation. In the monograph by Jackson [24], the integral (1) is presented under the name 'field integral over time.' Later, Bessonov in Ref. [25] proposed that electromagnetic fields be classified according to whether the value of (1) is zero or nonzero, and arrived at certain conclusions about the properties of fields with $\mathbf{S}_E \neq 0$; these conclusions, in our opinion, require corrections (see below). The term 'electric pulse area' was introduced in Ref. [26], which established an important role of this quantity in the electrodynamics of continuous media for a one-dimensional geometry, and later, Ref. [27] also did the same for the three-dimensional geometry (see also review [17]). Nevertheless, a discussion is still going on in the literature about the mere possibility of the existence of unipolar electromagnetic pulses, which, it is argued in some publications, contradict Maxwell's electrodynamic equations on the basis of judgments that are, in our opinion, unconvincing (see, e.g., Ref. [28]). The reason for the discussions, apart from terminological aspects, lies, on the one hand, in the unusual properties of unipolar pulses, which require clarification or reconsideration of some traditional views. On the other hand, theoretical work in most cases deals with rather simplified models and/or does not touch the formation process of such pulses. As far as experiments are concerned, they provide mainly qualitative information (see, for example, Refs [29–31]), and only recently has the electrical pulse area been measured quantitatively [32].

In a one-dimensional geometry (plane waves), the d'Alembert solution of the wave equation indicates that pulses of any shape, including unipolar, can propagate in a vacuum without changing shape. The propagation of unipolar pulses is also possible in a two-dimensional geometry [33]. However, the energy of such structures is infinite, because their transverse size is unlimited. It can be rigorously shown that in a three-dimensional geometry the propagation of pulses with nonzero electric area (and finite energy) is impossible in an unbounded vacuum that was always void of charges and matter [34, 35]. And yet, as pointed out in Ref. [36], one-dimensional propagation of such pulses is indeed possible, for example, in coaxial waveguides with no cutoff frequency (main waves) [37]. In this article, we demonstrate the compatibility of Maxwell's equations of electrodynamics with the existence of electromagnetic pulses localized in an unbounded space with nonzero electric area and finite energy. A central part, reflected in the title of this study, is the classical example of the field of a charge moving at a constant speed in a vacuum. We then consider the possibility of unipolarity (nonzero electric area) for transition radiation in the field of a pair of charges — a point dipole — and also in a more general situation of a system of charges moving in a vacuum.

2. Point charge uniformly moving in a vacuum

The electric field due to a charge q moving uniformly with a constant velocity V is [24, 38]

$$\mathbf{E} = \left(1 - \frac{V^2}{c^2}\right)\frac{q\mathbf{R}}{R^{*3}} \,. \tag{2}$$

Here,

$$\mathbf{R} = (x, y, z - Vt)\,, \quad R^{*2} = \left(1 - \frac{V^2}{c^2}\right) r_\perp^2 + (z - Vt)^2\,, \quad r_\perp^2 = x^2 + y^2\,. \tag{3}$$

As should be clear, the field and the flux of electromagnetic energy move uniformly together with the charge with velocity V along the z-axis. Field (2) can be treated qualitatively as the Coulomb field of the charge, which is flattened in the direction of its motion due to the relativistic effect [38]. The distribution of $\mathbf{E}$ is axisymmetric. In the cylindrical frame of reference $(r_\perp, \varphi, z)$,

$$E_r(r_\perp, z - Vt) = \left(1 - \frac{V^2}{c^2}\right)\frac{qr}{\left[(1 - V^2/c^2)\, r_\perp^2 + (z - Vt)^2\right]^{3/2}} \,. \tag{4}$$

Both the azimuthal and longitudinal components of the electric area are absent, $S_{E,\varphi} = S_{E,z} = 0$. Integrating (4) over time, we find for the radial component of the electric area

$$S_{E,r} = \frac{2q}{Vr_\perp} \,. \tag{5}$$

According to (5), the electric area does not depend on the longitudinal coordinate z and decreases in inverse proportion to the distance from the axis $r_\perp$. This quantity is also inversely proportional to the velocity of the charge motion [24], which in principle leads to the possibility of it having very large values (in a static limit $V \to 0$, the electric area tends to infinity). In the relativistic limit $V/c \to 1$, the electric area reaches its minimum $2q/(cr_\perp)$.

Note that the sign of the nonzero component of the electric area vector is constant (coinciding with the sign of the charge), so that a strictly unipolar pulse propagates through each point of the medium. The pulse duration τ at a point located at distance $r_\perp$ from the charge path will be determined by the level of $1/2$ of the maximum value of the radial component of the electric field (4). Then,

$$\tau = 2\sqrt{2^{2/3} - 1}\,\frac{\sqrt{1 - V^2/c^2}}{V}\, r_\perp \approx 1.533\,\frac{\sqrt{1 - V^2/c^2}}{V}\, r_\perp \,. \tag{6}$$

The numerical multiplier in (6) depends on the level used to define the pulse duration. From (6), it follows that the pulse duration is directly proportional to the detector distance $r_\perp$ from the charge trajectory (the z-axis) and decreases monotonically with increasing charge velocity V down to a zero value in the limit $V/c \to 1$; in a static limit ($V \to 0$), the pulse duration is infinite. It should also be mentioned that the radial direction of the electric area vector can facilitate the injection and propagation of unipolar pulses in coaxial waveguides.

The spectrum of such a pulse $\mathbf{E}_\omega = \int_{-\infty}^{+\infty} \mathbf{E} \exp(\mathrm{i}\omega t)\, \mathrm{d}t$ [24] may be of interest. For its components,

$$E_{z,\omega} = -2\mathrm{i}q\omega\left(\frac{1}{V^2} - \frac{1}{c^2}\right) K_0(\omega\beta) \exp\left(\frac{\mathrm{i}\omega z}{V}\right),$$

$$E_{r,\omega} = \frac{2q\omega}{V}\left(\frac{1}{V^2} - \frac{1}{c^2}\right)^{1/2} K_1(\omega\beta) \exp\left(\frac{\mathrm{i}\omega z}{V}\right). \tag{7}$$

Here, $\beta^2 = (1/V^2 - 1/c^2) r_\perp^2$ and $K_{0,1}$ are the cylindrical functions of the imaginary argument. In the limit $\omega \to 0$, we find $E_{z,0} = 0$, and, for $E_{r,0} = S_r$, the earlier value (5) follows. The spectrum $E_{r,\omega}$ is bell shaped, with the maximum at zero frequency and the characteristic width τ^{-1}.

In the case of relativistic charge motion $V^2/c^2 \to 1$, the pulse field tends to be transverse and, in this sense, it tends to the field in a vacuum without charges. This is the basis of the virtual photon method, in which the action of one charge on the other is replaced by the action of a purely electromagnetic pulse on the charge, which represents the field due to the other charge [24]. The possibility of detecting field pulses of moving charges due to the excitation of atoms corresponds to the experiments of Frank and Hertz [39].

Due to the constant velocity of the charge, there is no deceleration of the charge by radiation. We do not consider deceleration caused by the presence of a detector or a micro-object and their secondary radiation. The charge energy losses during the interaction with an object containing N nonrelativistic electrons with charge e and mass m can be estimated by the kinetic energy of the electrons acquired after the impact of the pulse, as $Ne^2S_E^2/(2m)$. These losses can be disregarded if they are substantially smaller than the initial energy of the relativistic charge.

In the example being considered, the entire field is moving at a constant speed V. The static part of the field is absent in this case, and the zero frequency component of the pulse spectrum (its electric area) cannot be interpreted as such. The question of whether such a structure can be considered a radiation pulse is rather terminological. It is often assumed that radiation accompanies only the accelerated motion of a charge [40], which takes place in the case considered in Refs [41–43]. An argument could be that the field of a uniformly moving charge is attached to it and is sort of its 'fur,' and only in the case of accelerated motion is a part of the field detached from the charge in the form of 'free' radiation. However, the electromagnetic field pulses associated with a uniformly moving charge will act on a micro-object or a detector in the same way as the pulses of radiation emitted by accelerating charges in their wave zone. In the first case, we are dealing with the motion of the charge and the associated field structure with respect to a stationary object (a detector), which cannot be eliminated by the Lorentz transformation (the electric area itself is not Lorentz invariant). We also mention that the pulses discussed here can be transformed into unipolar (with a nonzero electric area) for diffraction radiation [29, 30].

If a charge moves in a homogeneous linear medium with the dielectric permittivity ε, in the framework of classical electrodynamics, expression (5) for the electric area is replaced by

$$S_{E,r}^{(q)} = \frac{2q}{V\varepsilon r_\perp}\,. \tag{8}$$

The electrostatic value of ε should be used in (8), since the electric area corresponds to the zero-frequency spectral component. We mention the increase in the electric area in media in which ε is close to zero [44].

3. Transition radiation

The transition radiation discovered by Ginzburg and Frank [45] occurs even if a uniformly moving charge crosses an interface $z = 0$ between media with different electrodynamic properties. A large amount of the literature is devoted to this effect (see review [46]), reflecting its important applications. A detailed theory of transition radiation is given in Ref. [47]. In the case of nonmagnetic media with dielectric permittivities ε_1 and ε_2, the distribution of the electric area of the electromagnetic pulse is axisymmetric, and its nonzero components have the form [48]

$$S_{z,n}(r_\perp, z) = \frac{2q}{Vr\varepsilon_n}\,\frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2 + \varepsilon_1}\,, \quad r = \sqrt{r_\perp^2 + z^2}\,, \tag{9}$$

$$S_{r,n}(r_\perp, z) = \frac{2q}{Vr_\perp\varepsilon_n}\left[1 \mp \frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2 + \varepsilon_1}\left(1 - \frac{|z|}{r}\right)\right]. \tag{10}$$

Here, $n = 1, 2$ is the number of the medium related to the sign $+$ or $-$ on the right-hand side of (10), and static values are taken for the dielectric permittivities (at zero frequency). Note the appearance of the longitudinal electric area component (9), the sign of which is defined by the difference among the dielectric permittivities of the media. This component is localized near the interface and decays algebraically with distance from the interface. At such a distance, the magnitude of radial component (10) tends to the value (8) in each of the media, while in the transition region it is localized in the same way as the longitudinal component. A nonzero value of pulse electric area for transition radiation is also confirmed by the results of Ref. [31]. Let us recall that the radiation from colliding charges is also characterized by a nonzero value of the zero-frequency component in the field spectrum [38].

4. Point electric dipole

The model of a point dipole [49] describes two point charges of opposite signs q and $-q$ separated by the distance a in the limit $a \to 0$, $q \to \infty$, so that there is a finite limit $\lim_{a\to 0} qa = d$ called the dipole moment. The direction of the moment $\mathbf{d}$ is from the negative charge to the positive charge. The electric field of a linear dipole with a time-dependent d and fixed direction of $\mathbf{d}$ is given by the expression

$$\mathbf{E}(\mathbf{r}, t) = \left\{\frac{3[d]}{r^3} + \frac{3[\dot{d}]}{cr^2} + \frac{[\ddot{d}]}{c^2 r}\right\}(\mathbf{d}, \mathbf{n})\,\mathbf{n} - \left\{\frac{[d]}{r^3} + \frac{[\dot{d}]}{cr^2} + \frac{[\ddot{d}]}{c^2 r}\right\}\mathbf{d}\,, \tag{11}$$

where $\mathbf{r} = r\mathbf{n}$ is the vector of the coordinates of the observation point (the dipole is placed at the origin of the coordinates, the dots above d imply time differentiation, and the square brackets imply a retarded argument $t - r/c$.

Usually, in (11) only the terms proportional to r^{-1} are kept, which in turn are proportional to the derivative $\ddot{d}$ (far field). However, when calculating electric area, the terms with derivatives in (11) make a zero contribution, and only the near-field terms remain,

$$\mathbf{S}_E = \frac{3(\mathbf{d}, \mathbf{n})\,\mathbf{n} - \mathbf{d}}{r^3}\,D\,, \quad D = \int d(t)\,\mathrm{d}t\,. \tag{12}$$

It is seen that the distribution of the electric area is analogous to the distribution of the electric field of a static dipole. For a nonzero dipole moment $D \neq 0$, the electric area differs from zero, its distribution has an axial symmetry with the symmetry axis aligned with the dipole moment $\mathbf{d}$, and it decays with distance from the charge system as r^{-3}.

The integral dipole moment D can be found in the framework of the popular Lorentz oscillator model

$$\ddot{d} + \gamma\dot{d} + \omega_0^2 d = f(t)\,, \tag{13}$$

where γ is the decay coefficient for an oscillator with eigenfrequency ω_0 and $f(t)$ is the projection onto the dipole direction of an external force acting on the dipole charges; the force can be of various origins. Integrating (13), we find

$$D = \omega_0^{-2} S_f\,, \quad S_f = \int f(t)\,\mathrm{d}t\,. \tag{14}$$

Thus, in this model, in order to have a nonzero electric area for the dipole, it must be initialized by an excitation pulse with a nonzero area S_f. To determine the shape of the dipole field pulse, it is sufficient to use equation (13). Note that expression (14) does not include the damping coefficient γ, although the pulse duration depends on it. If the oscillator is nonlinear (there is an additional quadratic or cubic term on the left-hand side of (13)), the integral dipole moment D will differ from zero even for zero area S_f.

5. Electric area for a system of charges in a vacuum

Finally, we turn to a general case of electric charges moving in a vacuum (see also Refs [34, 41–43]). It should be recalled that, as pointed out in Ref. [27], the time integration of Maxwell's equation $\mathrm{rot}\,\mathbf{E} = -(1/c)(\partial\mathbf{B}/\partial t)$, where $\mathbf{B}$ is the magnetic field, for localized (with finite energy) radiating structures leads to the relation

$$\mathrm{rot}\,\mathbf{S}_E = 0\,. \tag{15}$$

The vector electric area field is therefore irrotational and potential with some 'potential' Φ_S such that

$$\mathbf{S}_E = -\mathrm{grad}\,\Phi_S\,. \tag{16}$$

In the one-dimensional (plane wave) geometry with propagation along the z-axis, expression (15) is formulated as the conservation of electric area

$$\frac{\mathrm{d}\mathbf{S}_E}{\mathrm{d}z} = 0\,. \tag{17}$$

Relationships (15) and (17) are rather general: they are valid for different media. A closed system of equations to determine the electric area is obtained using the material equation. For electric charges with density ρ in a vacuum, time integration of Maxwell's equation $\mathrm{div}\,\mathbf{E} = 4\pi\rho$ gives

$$\mathrm{div}\,\mathbf{S}_E = 4\pi Q\,, \tag{18}$$

where $Q(\mathbf{r}) = \int_{-\infty}^{\infty} \rho(\mathbf{r}, t)\,\mathrm{d}t$ is the integral charge density. Equations (15) and (18) are sufficient to determine the electric area given the distribution of the integral charge density. Formally, via the change of variables, they coincide with the main equations of electrostatics [37]. The potential Φ_S satisfies the Poisson equation

$$\Delta\Phi_S = -4\pi Q\,, \tag{19}$$

whose solution is written in the form

$$\Phi_S(\mathbf{r}) = \int \frac{Q(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|}\,\mathrm{d}\mathbf{r}'\,. \tag{20}$$

Note that equations (15)–(20) do not explicitly include the current density or the speed of light in a vacuum, so that the relativistic factors are not manifested here (but they do influence the character of the charge motion and charge density). It follows from (20) that a nonzero integral charge density in at least some spatial domain entails the appearance of a nonzero area of an electromagnetic pulse. The everywhere zero pulse area $\mathbf{S}(\mathbf{r}) \equiv 0$ is only possible if the integral charge density is everywhere zero, $Q(\mathbf{r}) \equiv 0$.

In the case of a point charge q moving straight along the z-axis with constant velocity V in a vacuum, we should write

$$\rho\,(x, y, z, t) = q\delta(x)\,\delta(y)\,\delta(z - Vt)\,,$$
$$Q = \left(\frac{q}{V}\right)\delta(x)\,\delta(y)\,. \tag{21}$$

Inserting (21) into (19) or (20) gives the earlier expression for the electric pulse area (8). Similarly, from (18) and (20), by taking the limit as described above, one can obtain expression (12) for the pulse area of a point dipole. Of interest is also the 'nonradiating' structure of the charge distribution as found in Ref. [34], where the field is completely confined to a finite domain (an analog of the static field in a spherical capacitor or anapole in a toroidal coil setup with a current [50]) and within a limited time interval.

The above-mentioned formal coincidence of the equations for the electric pulse ares with the equations of electrostatics allows finding the asymptotic form of the electric area in the far field, i.e., at distances greater than the size of the charge localization domain. To do this, solution (20) is expanded in multipole moments using the formula [37]

$$\frac{1}{|\mathbf{r} - \mathbf{r}'|} = \sum_{l=0}^{\infty} \frac{r'^l}{r^{l+1}}\,P_l\,\cos\chi\,, \tag{22}$$

where χ is the angle between the vectors $\mathbf{r}$ and $\mathbf{r}'$, $(\mathbf{r}, \mathbf{r}') = rr'\cos\chi$, and P_l are Legendre polynomials. Inserting (22) in (20), one gets the relationship

$$\Phi_S(\mathbf{r}) = \sum_{l=0}^{\infty} \frac{\Phi_l}{r^{l+1}}\,. \tag{23}$$

The explicit form of coefficients Φ_l is given in Ref. [37]. In the lowest order, the coefficient by the 'Coulomb' term takes the form

$$\Phi_0 = \int \mathrm{d}t \int \mathrm{d}\mathbf{r}\,\rho(\mathbf{r}, t) = \int Q_0\,\mathrm{d}t = \begin{cases} 0, & Q_0 = 0, \\ \infty, & Q_0 \neq 0\,. \end{cases} \tag{24}$$

Here, $Q_0 = \int \rho(\mathbf{r}, t)\,\mathrm{d}\mathbf{r}$ is the total electric charge of the system, which is constant in time, $\mathrm{d}Q_0/\mathrm{d}t = 0$. It follows from here, once again, that, for a nonzero system charge $Q_0 \neq 0$, the electric area is infinite and will further set $Q_0 = 0$. The Coulomb term in expansion (23) then drops out and the main contribution comes from the 'dipole' term

$$\Phi_{s1}(\mathbf{r}) = \frac{(\mathbf{d}_S, \mathbf{r})}{r^3}\,. \tag{25}$$

Expression (25) contains the 'dipole moment' of the integral charge distribution $\mathbf{d}_S = \int Q(\mathbf{r})\,\mathbf{r}\,\mathrm{d}\mathbf{r}$. From here, with the help of (16), we find the distribution of the electric area in the dipole approximation. Introducing the angle θ between the directions $\mathbf{r}$ and $\mathbf{d}_S$, we write in the vector form

$$\mathbf{S}_E = \frac{3(\mathbf{n}, \mathbf{d}_S)\,\mathbf{n} - \mathbf{d}_S}{r^3}\,. \tag{26}$$

This expression coincides, up to the notation, with the expression (12) for the pulse electric area of the point dipole field.

6. Conclusions

The simple electrodynamic models considered above can also be used for the classical description of the electromagnetic field in continuous media. New details on the interaction of extremely short pulses with micro-objects and media are introduced by quantum effects such as ionization and excitation of a considerable number of states. As far as radiation pulses are concerned, they cause additional energy losses that can be compensated by laser amplification [27]. These issues require further consideration. For us, however, it is important that the examples given here lend support to the reality of the existence of unipolar pulses from an electromagnetic field. The results may be important in formulating the requirements for superstrong electromagnetic field generation systems [51, 52].

Everywhere above, we have defined the electric area as the integral of the *total* electric field (1). After this work was accepted for publication, Ref. [35] appeared, which required comments [53]. The conclusion of [35] that the propagation of electromagnetic pulses with a nonzero electric area and finite energy is impossible in an unbounded vacuum without charges and media coincides with that of Ref. [34] obtained in a different way. The further generalization of this conclusion in Ref. [35] to the case where charges are present is connected with the subdivision of the total field, not strictly defined in Ref. [35], into the 'radiation field' and the 'static field' and the inclusion of the zero-frequency field component in the latter. The physical sense of such a subdivision is doubtful in many cases, because field detectors or objects interacting with the field cannot distinguish between these components. Furthermore, in the cases considered, the field is different from zero at each spatial location, i.e., it is noticeably above the noise only for a limited time interval (the pulse duration). Consequently, they lack a static component in the presence of which the electric area would become infinite. For a similar reason, the critiques in Ref. [35] of the experiment in Ref. [32], where a quantitative measurement of the electric area of an electromagnetic pulse is performed, seem to be unfounded.

One more recent work [54] casts doubts on the rule of electric area conservation (17). In fact, rule (17) is also valid under the conditions of Ref. [54], while its supposed violation is related to the use in [54] of equations in the approximation of unidirectional propagation [55] instead of the exact Maxwell's equations.

7. A few words on the 2023 Nobel Prize in Physics (added to the proofs)

The proofs of this paper arrived at the same time as the news that the 2023 Nobel Prize in Physics was awarded to Pierre Agostini, Ferenc Krausz, and Anne L'Huillier "for the experimental methods for the generation of *attosecond* light pulses for studies of electron dynamics in matter" [56]. We note that F Krausz is the coauthor of review [1] cited first in this paper. The 2023 prize commemorated a new important step in experimental physics compared to the experimental studies of atomic motion in chemical reactions using *femtosecond* laser pulses, marked by the 1999 Nobel Prize in Chemistry (awarded to Ahmed H Zevail [57]).

As far as fundamental physics is concerned, attosecond pulses, which are shorter than the Bohr period, make it possible, for example, to study experimentally the question of the observability of electron orbits in atoms. The significance of the achievement of the prize winners is emphasized by the advances in molecular physics, condensed-matter physics, chemistry, biology and other branches of science and technology made possible by the use of attosecond light pulses.

A key point in the new 'attosecond' science is the realization of radiation pulses with a duration that is smaller (shorter) than the time scale characteristic of the object of action. The method is based on the summation of many harmonics of laser radiation with multiple frequencies. Such pulses are multi-cycle: they contain a large number of field oscillation cycles.

In the scientific background to the award of the 2023 Nobel Prize in Physics, the Nobel Committee mentions the important contribution of other scientists to the development of attosecond science, including Paul Corkum and colleagues [58] and the subsequent work of the group of Ursula Keller [59], and Margaret Murnane, Henry Kapteyn, and collaborators [60]. In their research, they also used a relatively weak interaction of laser radiation with gases, accompanied by the generation of higher harmonics, but without exceeding the gas ionization threshold. The attosecond pulses are the result of coherent summation of these harmonics. These studies essentially use ideas developed by Leonid Veniaminovich Keldysh and the theory of photoionization in strong laser fields [61–66]. An important role in this stage of development was played by the work of other domestic scientists (see [4, 52, 67, 68] and others). However, the absence of ionization fundamentally limits the spectral width of the generated radiation and, respectively, the duration of the pulses by tens or hundreds of attoseconds.

Another approach, which is currently being developed, is based on the action of laser radiation of high (relativistic) intensity, exceeding 10^{18} W cm^{-2}, on solid targets [69–71]. In this case, the medium is ionized and a laser plasma is formed. As a result of the motion of the plasma charges in a strong laser field, a broad and relatively flat spectrum of secondary radiation is formed. In principle, this allows sequences of even shorter sub-attosecond (i.e, zeptosecond) radiation pulses to be formed [72–74]. Such pulses can be generated using free electron lasers [75].

A common feature of these approaches is that the generated pulses are multi-cycle, and thus bipolar. The electric field direction changes to the opposite one every half of the cycle. This weakens the effect of such pulses on micro-objects with a characteristic Bohr period that is smaller or comparable to the pulse duration. It is emphasized in this paper that, even if the possibilities of using progressively higher frequencies are exhausted, further pulse shortening is still possible by reducing the number of these cycles to one half cycle. Such short pulses become unipolar, so that their electric field acts on the charges unidirectionally and therefore most efficiently. This efficiency is not determined by the energy or the maximum pulse intensity, but by the pulse electric area (see formula (1) above).

It seems that further research on the generation of extremely short electromagnetic pulses with a significant electric area will lead to further progress in the diagnostics of rapidly changing processes and phenomena, and in the action on their dynamics.

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