On the Physical Origin of the Invariance of the Speed of Light

Oleh Kozyrko
Mykolaiv, Ukraine
ok@okozyrko.com

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Problem Statement

The independence of the speed of light from the motion of its source is a fundamental property of the electromagnetic field. In existing theories — classical electrodynamics, special relativity, and quantum electrodynamics — this property is fixed either as a postulate or as a consequence of the mathematical structure of the theory. However, none of these frameworks provides a physical explanation of the origin of this phenomenon; that is, they do not describe the physical process through which the speed of light becomes independent of the velocity of its source.

Core Thesis

The invariance of the speed of light with respect to the motion of its source arises from the fact that emission is realized as a quantum transition involving a discrete change in the state of the system. After this transition, the resulting configuration of the electromagnetic excitation is governed by the equations of the free field. The dynamics of the free field do not contain parameters characterizing the kinematic state of the source, which ensures that the subsequent propagation of the excitation does not depend on the source's velocity and is determined solely by the intrinsic structure of the free-field equations.

Implications

In quantum electrodynamics, the emission of a photon is not treated as an extended process but as a quantum transition described by the interaction operator and accompanied by a discrete change in the state of the quantum system and its associated electromagnetic field.

This transition is represented schematically as

$$| E_2\rangle \;\longrightarrow\; | E_1\rangle + | \gamma(\omega)\rangle,$$

where $| \gamma(\omega)\rangle$is interpreted as an elementary excitation of the electromagnetic field in a given mode. The transition fixes the distinction between the "before" and "after" states of the system within the standard formalism of quantum field theory; this distinction arises from the locality of the interaction and is unaffected by subsequent external influences, reflecting the causal completeness of the quantum event.

Once the transition is completed, several physical aspects can be identified:

(a) Energy transition
The system undergoes a discrete change of its internal state:

$$| E_2\rangle \rightarrow | E_1\rangle.$$

(b) Fixation of the source state
The source is left in a new eigenstate determined by its Hamiltonian.

(c) Emergence of a field quantum
An excitation of the electromagnetic field is created, described by $|\gamma(\omega)\rangle$, without invoking any classical trajectory-based interpretation.

(d) Transition to free-field evolution
After the interaction ends, the subsequent evolution of the excitation is governed by the Hamiltonian of the free field; the associated four-potential A^{μ}satisfies the free-field equation, and this evolution no longer depends on the properties of the source.

Thus, the system's dynamics can be naturally divided into two stages:

1) Coupled phase

The source and the field constitute a single quantum system in which the transition $|E_2\rangle \to |E_1\rangle$ occurs. At this stage, the properties of the future excitation depend on the initial state of the source through the interaction operator.

2) Free-propagation phase

After the transition is completed, the excitation of the electromagnetic field is described by the free-field equation

$$\Box A^{\mu} = 0,$$

which contains no parameters characterizing the source's kinematics (velocity, acceleration, direction of motion). Consequently, the further evolution of the formed excitation is determined solely by the intrinsic properties of the relativistic wave operator and does not depend on the parameters of the source.

Conclusion

This work proposes a physically motivated explanation for the independence of the speed of light from the motion of its source, based on analyzing the speed of light as a result of the transition from a regime of local quantum interaction to the autonomous dynamics of the free electromagnetic field. Such an interpretative distinction does not alter the formalism of quantum electrodynamics but reveals the mechanism by which the propagation speed of the electromagnetic excitation becomes independent of the kinematic properties of the system that produced it. In this framework, the invariance of the speed of light appears not as a postulated property or solely as a consequence of symmetry principles, but as a direct physical consequence of the transition from interacting dynamics to the autonomous free-field dynamics.

Accordingly, the work formulates an interpretation of the invariance of the speed of light that has not been presented in the existing literature. It is based on the transition from the emission phase to the autonomous phase of free-field evolution, whose dynamics do not depend on the kinematic parameters of the source. In this interpretation, the invariance of the speed of light acquires a physical justification as a consequence of the change of dynamical regimes of the quantum system, rather than only as an axiomatically assigned and experimentally confirmed property of the theory.