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# Nonlocal electrodynamics of accelerated systems

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**Abstract**

Acceleration-induced nonlocality is discussed and a simple field theory of nonlocal electrodynamics is developed. The theory involves a pair of real parameters that are to be determined from observation. The implications of this theory for the phenomenon of helicity-rotation coupling are briefly examined.
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## 1. Introduction

Consider the measurement of a basic *radiation* field $\psi$ by an accelerated observer in Minkowski spacetime. According to the hypothesis of locality [1], the observer, at each event along its worldline, is locally equivalent to an otherwise identical momentarily comoving inertial observer. The frame of this hypothetical inertial observer is related to the background global inertial frame via a Poincaré transformation; therefore, the field measured by the momentarily comoving observer is $\widehat{\psi}(\tau) = \Lambda(\tau)\psi(\tau)$, where $\tau$ is the observer's proper time at the event under consideration and $\Lambda(\tau)$ is a matrix representation of the Lorentz group.

Let $\widehat{\Psi}$ be the field that is actually measured by the accelerated observer. The hypothesis of locality requires that $\widehat{\Psi}(\tau) = \widehat{\psi}(\tau)$. However, the most general linear relation between $\widehat{\Psi}(\tau)$ and $\widehat{\psi}(\tau)$ consistent with causality is [2]

$$\widehat{\Psi}(\tau) = \widehat{\psi}(\tau) + \int_{\tau_0}^{\tau} K(\tau, \tau')\widehat{\psi}(\tau')\,\mathrm{d}\tau', \tag{1}$$

where $\tau_0$ is the initial instant at which the observer's acceleration is turned on. The manifestly Lorentz-invariant ansatz (1) involves a kernel that must be proportional to the acceleration of the observer. The kernel is determined from the postulate that a basic *radiation* field can never stand completely still with respect to an accelerated observer. This is simply a generalization of the standard result for inertial observers. A detailed analysis reveals that the only physically acceptable kernel consistent with this physical requirement is [3–6]

$$K(\tau, \tau') = k(\tau') = -\frac{\mathrm{d}\Lambda(\tau')}{\mathrm{d}\tau'}\Lambda^{-1}(\tau'). \tag{2}$$

Using this kernel, Eq. (1) may be written as

$$\widehat{\Psi}(\tau) = \widehat{\psi}(\tau_0) - \int_{\tau_0}^{\tau} \Lambda(\tau')\frac{\mathrm{d}\psi(\tau')}{\mathrm{d}\tau'}\,\mathrm{d}\tau'. \tag{3}$$

An immediate consequence of this relation is that if the accelerated observer passes through a spacetime region where the field $\psi$ is constant, then the accelerated observer measures a constant field as well, since $\widehat{\Psi}(\tau) = \widehat{\psi}(\tau_0)$. This is the main property of kernel (2) and it will be used in the following section to argue that in nonlocal electrodynamics, Eq. (2) is only appropriate for the electromagnetic potential.

The basic notions that underlie this nonlocal theory of accelerated observers appear to be consistent with the quantum theory [7–9]. Indeed, such an agreement has been the main

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goal of the nonlocal extension of the standard relativity theory of accelerated systems [10,11]. Moreover, the observational consequences of the theory are consistent with experimental data available at present. On the other hand, our treatment of nonlocal electrodynamics has thus far emphasized only *radiation* fields. However, a nonlocal field theory of electrodynamics must also deal with special situations such as electrostatics and magnetostatics. Furthermore, the application of our nonlocal theory to electrodynamics encounters an essential ambiguity: should the basic field $\psi$ be identified with the vector potential $A_\mu$ or the Faraday tensor $F_{\mu\nu}$? In our previous treatments [10,12], this ambiguity was left unresolved, since for the issues at hand either approach seemed to work. Nevertheless our measurement-theoretic approach to acceleration-induced nonlocality could be more clearly stated in terms of the directly measurable and gauge-invariant Faraday tensor, which was therefore preferred [10,12].

The main purpose of the present work is to resolve this basic ambiguity in favor of the vector potential. The physical reasons for this choice are discussed in the following section. Section 3 is then devoted to the determination of the appropriate kernel for the nonlocal Faraday tensor. Section 4 deals with the consequences of this approach for the phenomenon of spin-rotation coupling for photons. The results are briefly discussed in Section 5.

## 2. Resolution of the ambiguity

It is a consequence of the hypothesis of locality that an accelerated observer carries an orthonormal tetrad $\lambda^\mu{}_{(\alpha)}$. The manner in which this local frame is transported along the worldline reveals the acceleration of the observer; that is,

$$\frac{d\lambda^\mu{}_{(\alpha)}}{d\tau} = \phi_\alpha{}^\beta \lambda^\mu{}_{(\beta)}, \tag{4}$$

where $\phi_{\alpha\beta} = -\phi_{\beta\alpha}$ is the antisymmetric acceleration tensor.

Let us now consider the determination of an electromagnetic field, with vector potential $A_\mu$ and Faraday tensor $F_{\mu\nu}$,

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu, \tag{5}$$

by the accelerated observer. The measurements of the momentarily comoving inertial observers along the worldline are given by

$$\widehat{A}_\alpha = A_\mu \lambda^\mu{}_{(\alpha)}, \qquad \widehat{F}_{\alpha\beta} = F_{\mu\nu}\lambda^\mu{}_{(\alpha)}\lambda^\nu{}_{(\beta)}. \tag{6}$$

Thus according to our basic ansatz [2], the fields as measured by the accelerated observer are

$$\widehat{\mathcal{A}}_\alpha(\tau) = \widehat{A}_\alpha(\tau) + \int_{\tau_0}^{\tau} K_\alpha{}^\beta(\tau,\tau')\widehat{A}_\beta(\tau')\,d\tau', \tag{7}$$

$$\widehat{\mathcal{F}}_{\alpha\beta}(\tau) = \widehat{F}_{\alpha\beta}(\tau) + \int_{\tau_0}^{\tau} K_{\alpha\beta}{}^{\gamma\delta}(\tau,\tau')\widehat{F}_{\gamma\delta}(\tau')\,d\tau'. \tag{8}$$

Though these relations may be reminiscent of the phenomenological memory-dependent electrodynamics of certain continuous media [13], they do in fact represent field determinations in vacuum and are consistent—in the case of kernels (9) and (11) specified below—with the averaging viewpoint developed by Bohr and Rosenfeld [14].

It remains to determine the kernels in Eqs. (7) and (8). Specifically, which one should be identified with the result given in Eq. (2)? The aim of the following considerations is the construction of the simplest tenable nonlocal electrodynamics; however, there is a lack of definitive experimental results that could guide such a development. We must therefore bear in mind the possibility that future experimental data may require a revision of the theory presented in this Letter.

Let us recall here the main property of kernel (2) noted in the previous section: a uniformly moving observer enters a region of constant field $\psi$; the observer is then accelerated, but it continues to measure the same constant field. Now imagine such an observer in an extended region of constant electric and magnetic fields; we intuitively expect that as the velocity of the observer varies, the electromagnetic field measured by the observer would in general vary as well. This expectation appears to be provisionally consistent with the result of Kennard's experiment [15,16]. It follows that the kernel in Eq. (8) cannot be of the form given in Eq. (2). On the other hand, in a region of constant vector potential $A_\mu$, the gauge-dependent potential measured by an arbitrary accelerated observer could be constant; in fact, in this region the gauge-invariant electromagnetic field vanishes for all observers by Eqs. (5), (6) and (8). Therefore, we assume that the kernel in Eq. (7) is of the form given by Eq. (2), so that

$$K_\alpha{}^\beta(\tau,\tau') = k_\alpha{}^\beta(\tau'), \tag{9}$$

which can be expressed via Eqs. (2) and (4) as

$$k_\alpha{}^\beta = -\phi_\alpha{}^\beta. \tag{10}$$

The determination of the field kernel in Eq. (8) is the subject of the next section.

## 3. Field kernel

The first step in the determination of the kernel in Eq. (8) is to require that

$$K_{\alpha\beta}{}^{\gamma\delta}(\tau,\tau') = k_{\alpha\beta}{}^{\gamma\delta}(\tau'). \tag{11}$$

This simplifying assumption is rather advantageous [4–6]. If the acceleration of the observer is turned off at $\tau = \tau_f$, then the new kernel vanishes for $\tau > \tau_f$. In this case, the nonlocal contribution to Eq. (8) is a constant memory of the past acceleration of the observer that is in principle measurable. This constant memory is simply canceled in a measuring device whenever the device is reset.

Next, we assume that $k_{\alpha\beta}{}^{\gamma\delta}$ is linearly dependent upon the acceleration tensor $\phi_{\alpha\beta}$. Clearly, the basic notions of the nonlocal theory cannot a priori exclude terms in the kernel that would be nonlinear in the acceleration of the observer. Therefore, our linearity assumption must be regarded as preliminary and contingent upon agreement with observation.

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