The Enigmatic Photon

Volume 5: O(3) Electrodynamics

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KLUWER ACADEMIC PUBLISHERS
DORDRECHT / BOSTON / LONDON

Paper 16

$\boldsymbol{B}^{(3)}$ Echoes

It is shown that the $\boldsymbol{B}^{(3)}$ field of vacuum electromagnetism regenerates itself throughout spacetime from repeated gauge transforms. These $\boldsymbol{B}^{(3)}$ *echoes* are physical magnetic fields which can be detected experimentally in principle through optical analogues of the Aharonov-Bohm effect.

Key words. Optical Aharonov-Bohm effect, action at a distance, $\boldsymbol{B}^{(3)}$ field

16.1 Introduction

The existence of the $\boldsymbol{B}^{(3)}$ field is established [1—12] by that of magneto-optic effects typified by the well-verified [13—21] inverse Faraday effect. In this note it is argued that the field is echoed throughout space-time by repeated gauge transformations into the vacuum of $\boldsymbol{A}$, where,

$$\boldsymbol{B}^{(3)} := \nabla \times \boldsymbol{A} = -i\frac{e}{\hbar}\boldsymbol{A}^{(1)} \times \boldsymbol{A}^{(2)}, \qquad (2.16.1)$$

defines the original $\boldsymbol{B}^{(3)}$ in vacuo in a local region of space-time. Here $\boldsymbol{A}^{(1)} = \boldsymbol{A}^{(2)*}$ is a plane wave potential, a solution of the d'Alembert wave equation, and complex [1—12]. Thus, the conjugate product $\boldsymbol{A}^{(1)} \times \boldsymbol{A}^{(2)}$ is pure imaginary. In the complex space basis ((1), (2), (3)), $\boldsymbol{B}^{(3)}$ is pure real and observable [1—12]. Here $\hbar / e$ is the elementary fluxon (weber) where $\hbar$ is Dirac's constant and e the charge quantum.

The $\boldsymbol{B}^{(3)}$ echoes, in analogy with the Aharonov-Bohm effects [22—25], are physical observables (magnetic flux densities) in regions of space-time where the original $\boldsymbol{B}^{(3)}$ is zero. They can therefore be observed experimentally by carefully excluding the electromagnetic field from direct contact with the sample (for example electrons). Non simply connected vacuum topology [22—25] then supports the existence of non-local effects which are measurable. It is speculated that $\boldsymbol{B}^{(3)}$ echoes might, if observed, be evidence for action at a distance in electromagnetism.

16.2 The Gauge Transformation

Since $\boldsymbol{B}^{(3)}$ is a physical magnetic field it can always be expressed in Eq. (2.16.1) as the curl of a vector potential $\boldsymbol{A}$. The gauge transformation [26],

$$\boldsymbol{A} \rightarrow \boldsymbol{A} + \nabla \phi, \tag{2.16.2}$$

where ϕ is a flux in weber, leaves $\boldsymbol{B}^{(3)}$ unaffected if defined as the curl of $\boldsymbol{A}$. It is therefore invariant under gauge transformation. Since $\boldsymbol{A}^{(1)} \times \boldsymbol{A}^{(2)}$ is an experimental observable [13—21] it is also invariant under gauge transformation. It follows that,

$$\nabla^{(1)} := -i \frac{e}{\hbar} \boldsymbol{A}^{(1)}, \tag{2.16.3}$$

must be regarded as an operator, and that $\boldsymbol{A}^{(2)}$ must be regarded as a vector potential. Equation (2.16.3) is one of the quantum postulates [1—3], i.e., momentum in quantum mechanics is a del operator within a factor $i\hbar$ [22].

The product $A^{(1)} \times A^{(2)}$ is invariant for example under a gauge transform such as,

$$A^{(2)} \rightarrow A^{(2)} + \nabla^{(1)}\phi, \qquad \nabla^{(1)}\phi := A^{(1)}, \tag{2.16.4}$$

in which the del operator is not changed. The del operator is not changed, of course, under the ordinary gauge transform (2.16.2).

In a local region of the vacuum where both A and $B^{(3)}$ are zero, the potential function $\nabla\phi$ is non-zero in general and causes the Aharonov-Bohm effects [22—25]. These are understood as being due to the fact that the vacuum is structured [22]. Recently, optical equivalents of the Aharonov-Bohm effect have been suggested [1—3] and worked out theoretically. Since $\nabla\phi$ is complex and periodic, its conjugate $(\nabla\phi)^*$ is also non-zero, and so there exists the $B^{(3)}$ echo,

$$B_1^{(3)} = -i\frac{e}{\hbar}(\nabla\phi) \times (\nabla\phi)^*, \tag{2.16.5}$$

in regions of the vacuum where $B^{(3)}$ itself is zero experimentally. If $B^{(3)}$ is a magnetic field, then so is $B_1^{(3)}$, and the latter is real, physical, and therefore observable in principle. The process can be continued by gauge transformation on the first echo $B_1^{(3)}$,

$$B_1^{(3)} := \nabla \times A_1, \qquad A_1 \rightarrow A_1 + \nabla\phi_1, \tag{2.16.6}$$

thus defining the second echo in regions of the vacuum where both $B^{(3)}$ and $B_1^{(3)}$ are zero experimentally. This process, if continued, gives an infinite number of echoes,

$$B_1^{(3)}, \;...., \; B_n^{(3)}, \qquad n \rightarrow \infty, \tag{2.16.7}$$

which are supported by non-simply-connected vacuum topology [22—25], and are all present in space-time irrespective of any consideration of signal velocity c.

16.3 Non-locality; Action at a Distance

The concept of non-locality can therefore be explained by gauge transforms of this nature, and such an explanation supports the interpretation of quantum mechanics by Bohm and others [26,27]. Although the original $\boldsymbol{B}^{(3)}$ is unchanged by the gauge transform, the $\boldsymbol{B}^{(3)}$ echo is produced nevertheless in a region of space-time where $\boldsymbol{B}^{(3)}$ is zero (for example outside a fibre or waveguide, Sec. 16.4). Similarly the $\boldsymbol{B}_1^{(3)}$ echo produces the $\boldsymbol{B}_2^{(3)}$ echo and so forth for $n \to \infty$. Therefore the field $\boldsymbol{B}^{(3)}$ is influential in regions infinitely remote from its original locality. This appears to be the first indication of non-locality in an electromagnetic field component rather than in gauge transformed potentials, as in the original Aharonov-Bohm effect [22—25]. Assuming that the field is non-local in this way, its influence is felt in remote regions of space-time without transmittal by a signal velocity, which for the hypothetically massless photon is c. This may therefore be action at a distance, one of a class of superluminal phenomena [28] in electromagnetism. Interestingly, Chubykalo and Smirnov-Rueda [29] have demonstrated the existence of longitudinal solutions of the Maxwell equations in vacuo which involve superluminal and subluminal exponents from the wave equation. Muñera and Guzmán [30] have shown that the reduction of the Maxwell equations to the d'Alembert equation produces a class of longitudinal solutions in vacuo provided that the scalar potential is phase dependent. The $\boldsymbol{B}^{(3)}$ field is therefore an example of a physical longitudinal solution in vacuo with zero phase, and for this reason has the special property of being proportional to the physically observable conjugate product. Gauge transformation of the latter must therefore take place in such a way as to preserve the physical nature of $\boldsymbol{B}^{(3)}$, and as we have seen, this leads to field non-locality (*echoes*), as opposed to potential non-locality.

16.4 Experimental Investigation

A clear experimental demonstration of non-locality in $\boldsymbol{B}^{(3)}$ can be achieved in principle by observing the inverse Faraday effect in regions where the field is excluded. In order to estimate the magnitude of the effect it is sufficient to use a simple classical demonstration based on the relativistic Hamilton-Jacobi equation [1—3] to show the influence of $\boldsymbol{B}^{(3)}$ on one electron. The quantum equivalent of the effect is based on the Dirac equation.

The original inverse Faraday effect was shown by Talin *et al.* [31] to be explicable in terms of the classical, relativistic Hamilton-Jacobi equation. The theory has been developed in terms of $\boldsymbol{B}^{(3)}$ [1] and shows that the energy of interaction of an electron in a circularly polarized electromagnetic field is,

$$\Delta En = \frac{e^2c^2}{\omega}\left(\frac{B^{(0)}}{(m^2\omega^2 + e^2B^{(0)2})^{1/2}}\right)|\boldsymbol{B}^{(3)}| \,, \tag{2.16.8}$$

where $\boldsymbol{B}^{(3)} = B^{(0)}\boldsymbol{e}^{(3)}$. Here ω is the field angular frequency and m the mass of the electron. The electronic properties in the interaction energy are e and m; the field properties are ω, c and $B^{(0)}$, the magnitude of $\boldsymbol{B}^{(3)}$ [1]. The plane wave $\boldsymbol{A}^{(1)}$ is a solution of the vacuum d'Alembert equation. In this case, $B^{(0)} = \kappa A^{(0)} = \omega A^{(0)}/c$ [1—3], where $\kappa = \omega/c$ is the wavenumber in vacuo. Equation (2.16.8) becomes,

$$\Delta En = \frac{e^2A^{(0)2}c}{(m^2c^2 + e^2A^{(0)2})^{1/2}} \,. \tag{2.16.9}$$

In the limit $eA^{(0)} \gg mc$, Eq. (2.16.9) becomes $\Delta En \rightarrow eA^{(0)}c = \hbar\omega$; using the free photon minimal prescription [1—3] $\hbar\kappa = eA^{(0)}$. In this limit, the photon $\hbar\omega$ is transferred to the electron, and annihilated. This is the high field limit [3]. In the opposite low field limit, $eA^{(0)} \ll mc$, the inverse Faraday effect is,

$$\Delta En \rightarrow \frac{e^2}{m} A^{(0)2} = \frac{(\hbar\omega)^2}{mc^2} = \left(\frac{\hbar\omega}{mc^2}\right)\hbar\omega. \qquad (2.16.10)$$

This limit is attained experimentally using visible frequencies, the opposite high field limit using radio frequencies [1—3]. In Eq. (2.16.10), the inverse Faraday effect is seen to be the square of the quantum of electromagnetic energy (i.e., photon squared) divided by the electronic rest energy, mc^2; and is simply the energy transferred inelastically ($\hbar\omega/mc^2 < 1$) in photon-electron collisions. The existence of the effect was first inferred thermodynamically and phenomenologically by Pershan [32], and it was first demonstrated empirically using the induction due to $\boldsymbol{B}^{(3)}$ [13]. If $B^{(0)} = \kappa A^{(0)}$ and if $\boldsymbol{B}^{(3)*} = B^{(0)}\boldsymbol{e}^{(3)*} = \nabla \times \boldsymbol{A}$ in Eq. (2.16.1), then $A^{(0)}$ is the magnitude of $\boldsymbol{A}$; and $B^{(0)} = eA^{(0)2}/\hbar$. Therefore,

$$B^{(0)} = |\boldsymbol{B}^{(3)}| = |\nabla \times \boldsymbol{A}| = \frac{e}{\hbar} A^{(0)2} = \kappa A^{(0)} = \frac{\omega}{c} A^{(0)}, \qquad (2.16.11)$$

and in regions where $\boldsymbol{B}^{(3)}$ and $\boldsymbol{A}$ are non-zero they are related by

$$B^{(0)} = |\nabla \times \boldsymbol{A}| = |\nabla \times (\boldsymbol{A} + \nabla\phi)|. \qquad (2.16.12)$$

The flux density $B^{(0)}$ creates in addition an inverse Faraday effect in regions where $\boldsymbol{B}^{(3)*}$ and $\boldsymbol{A}$ are zero. This effect is due to $\boldsymbol{B}^{(3)*} = -i\,(e/\hbar)\,(\nabla\phi) \times (\nabla\phi)^*$. The total flux density present in both regions is however, still $B^{(0)}$. In order to see this effect experimentally the standard inverse Faraday experiment [13—21] is modified by excluding the electromagnetic field from direct contact with the electrons. For example, a laser beam in an optical fibre is directed through an electron beam and the inverse induction measured with an induction coil. Observation of this effect would prove action at a distance in electromagnetism, and by implication, gravitation [33].

The total magnetic flux density present is always given by the curl of a sum of potential functions,

$$B^{(3)} = \nabla \times (A + A_1 + \ldots) = \nabla \times A . \tag{2.16.13}$$

When A and $B^{(3)}$ are both zero, the balance of terms in Eq. (2.16.13) is represented by

$$0 = 0 + \nabla \times A_1 + \ldots \tag{2.16.14}$$

where,

$$A_1 \neq 0, \quad A_1 \times A_1^* \neq 0 . \tag{2.16.14a}$$

Therefore $\nabla \times A_1$ is always zero, but $-A_1^* \times A_1$ is non-zero; and ∇ is not equal to $ieA_1^*/\hbar$. The net result of the gauge transform is therefore,

$$B^{(3)} \rightarrow B_1^{(3)} \rightarrow B_2^{(3)} \text{ etc.,} \tag{2.16.15}$$

i.e., to topologically transfer $B^{(3)}$ from one region of space-time to another. In so doing, the total magnitude $B^{(3)}$ is conserved by Noether's theorem. The magnitude of the expected inverse Faraday effect is therefore the same, outside or inside the fibre.

Acknowledgments

York University, Toronto and the Indian Statistical Institute, Calcutta, are thanked for visiting professorships, and e mail discussions acknówledged with several colleagues worldwide.

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