Vector and Scalar Potentials, Advanced and Retarded Waves and Nonlocal Phenomena

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The issue of whether Bell's theorem and other remote connectedness phenomena, such as Young's double slit experiment, demands superluminal or space-like signals or prior generated luminal signals is an area of hot debate. This also relates to the existence of advanced vs. retarded potentials and annihilation creation operators which are of interest in this regard. Using the complex model of A^{μ} we will examine the issue of the nonlocality of Bell's theorem as quantum mechanical 'transactions' providing a microscopic communication path between detectors across space-like intervals, which violate the EPR locality postulate [1]. See Chap. 4. This picture appears consistent with the remote connectedness properties of complex Minkowski space. Also, there are implications for macroscopic communications channels; another area of debate. Detailed discussions of Bell's theorem are given in [2].

1. Vector and Scalar Potentials and Fields

We formulate fields in terms of A or $\underset{\sim}{A} = (A^j, \phi)$ where A^j is $\underline{A}$ rather than the tensor, $F_{\mu\nu}$ or $\underline{E}$ or $\underline{B}$. We proceed from the usual continuity equation $\nabla \cdot \underline{J} + \partial\rho / \partial t = 0$ and utilize the expression $F_{\mu\nu} = \partial A_\nu / \partial x_\mu - \partial A_\mu / \partial x_\nu$. For the usual retarded potentials then, we have the Lorentz condition

$$\nabla \cdot \underline{A} + \mu\varepsilon \frac{\partial \varphi}{\partial t} = 0 \quad \text{and} \quad \nabla^2 \underline{A} - \mu\varepsilon \frac{\partial^2 \underline{A}}{\partial t^2} = -\mu \underline{J} \tag{1}$$

We also derive

$$\nabla^2 \phi - \mu\varepsilon \frac{\partial^2 \phi}{\partial t^2} = -\frac{1}{\varepsilon}\rho \tag{2}$$

Equations (1) and (2) are the usual retarded potential solutions. The radiation field in quantum electrodynamics (QED) is usually quantized in terms of (A, φ). Conversion back to the $\underline{E}$ and $\underline{B}$ fields can be performed using $\underline{E} = -\nabla\varphi - \partial\underline{A}/\partial t$ and $\underline{B} = \nabla \times \underline{A}$. Quantization of the field consists of regarding the phase space coordinates (*x, k*) or (*q, p*) as quantum mechanical coordinates of a set of equivalent harmonic oscillators using the variables of $p = E/c = \hbar\omega/c$ and $c = \lambda\omega$ so that $k = n\omega/c$. [3]. Using the second quantized method and treating k_r, q_r and A_r as quantum numbers then we have quantized allowable energy levels n_r and η_r such as $W = \sum_r (n_r + \eta_r)\hbar\omega_r$ for two quantum states, n and η. Solutions are given in the form

$$\Psi \propto \sum_{n_r} n_r \exp - \left[\frac{iW(n_r)}{\hbar} \right] \tag{3}$$

and we have a Hamiltonian equation of motion $\dot{p}_{ab} + (ck)^2 q_{ab} = 0$ or $\dot{q}_{ab} = p_{ab}$ and for its Hamiltonian

$$H = \tfrac{1}{2} \sum [p_{ab}^2 + (ck)^2 q^2 q_{ab}^2]. \tag{4}$$

The electromagnetic field energy of the volume integral $(E^2 + B^2)/8\pi$ is just equal to the Hamiltonian.

We examine such phenomena as absorption and polarization in terms of the complexification of $\underline{E}$ and $\underline{B}$ or $\underline{A}$ and ϕ. Defining the usual $D = \varepsilon E$ (for displacement field) and $B = \mu H$ are performed for a homogeneous isotopic media. If we introduce p_0 and m_0 as independent of $\underline{E}$ and $\underline{H}$ where the induced polarizations of the media are absorbed into the parameters ε and μ, we have

$$D = \varepsilon E + p_0 \quad \text{and} \quad H = \tfrac{1}{\mu} B - m_0 \tag{5}$$

Then we define a complex field as

$$\underline{Q} \equiv \underline{B} + i\sqrt{\varepsilon\mu}\,\underline{E} \tag{6}$$

so that we have Maxwell's equations now written as

$$\nabla \times \underline{Q} + i\sqrt{\varepsilon\mu} \frac{\partial \underline{Q}}{\partial t} = \mu \underline{J} \quad \text{and} \quad \nabla \cdot \underline{Q} = i\sqrt{\frac{\mu}{\varepsilon}}\rho \tag{7}$$

Using vector identities [3] and resolving into real and imaginary parts, we have

$$\nabla^2 \underline{H} - \varepsilon\mu \frac{\partial^2 \underline{H}}{\partial t^2} = -\nabla \times \underline{J} \quad \text{and} \quad \nabla^2 \underline{E} - \varepsilon\mu \frac{\partial \underline{E}}{\partial t^2} = \mu \frac{\partial \underline{J}}{\partial t} + \frac{1}{\varepsilon}\nabla\rho \tag{8}$$

for the magnetic and electric fields.
We define Q in terms of the complex vector potential that $A_{\text{Re}} \to V_{\text{complex}}$ and $\phi_{\text{Re}} \to \varphi_{\text{complex}}$ where V is the complex potential as a vector-like quantity. Then

$$\underline{Q} = \nabla \times \underline{V} - i\sqrt{\varepsilon\mu} \frac{\partial \underline{V}}{\partial t} - i\sqrt{\varepsilon\mu}\nabla\varphi \tag{9}$$

subject to the condition similar to before, $\nabla \cdot \underline{V} + \varepsilon\mu \,{\partial \varphi}/{\partial t} = 0$. Then

$$\nabla^2 \underline{V} - \varepsilon\mu \frac{\partial^2 \underline{V}}{\partial t^2} = -\mu \underline{J} \text{ and } \nabla^2 \varphi - \varepsilon\mu \frac{\partial^2 \varphi}{\partial t^2} = -\frac{1}{\varepsilon}\rho \qquad (10)$$

Separation into real and imaginary parts of these potentials, $\underline{V}$ and ϕ can be written as

$$\underline{V} = \underline{A}_{\mathrm{Re}} - i\sqrt{\frac{\mu}{\varepsilon}}\underline{A}_{\mathrm{Im}} \text{ and } \varphi = \phi_{\mathrm{Re}} - i\sqrt{\frac{\mu}{\varepsilon}}\phi_{\mathrm{Im}} \qquad (11)$$

Upon substitution into the equation for Q and separation into real and imaginary parts we have

$$\begin{aligned} \underline{B}_{\mathrm{Re}} &= \nabla \times \underline{A}_{\mathrm{Re}} - \frac{\mu \partial \underline{A}_{\mathrm{Im}}}{\partial t} - \mu \nabla \phi_{\mathrm{Im}}; \\ \underline{E}_{\mathrm{Re}} &= -\nabla \phi_{\mathrm{Re}} - \frac{\partial \underline{A}_{\mathrm{Re}}}{\partial t} - \frac{1}{c}\nabla \times \underline{A}_{\mathrm{Im}} \end{aligned} \qquad (12)$$

The usual equations for the fields result when A_{Im} and ϕ_{Im} are taken as zero.

If free currents and charges are everywhere zero in the region under consideration, then we have

$$\nabla \times \underline{Q} + i\sqrt{\varepsilon\mu}\frac{\partial \underline{Q}}{\partial t} = 0 \text{ and } \nabla \cdot \underline{Q} = 0 \qquad (13)$$

and we can express the field in terms of a single complex Hertzian-like vector $\underline{L}$ as the solution of

$$\nabla^2 \underline{L} - \varepsilon\mu \,{\partial^2 \underline{L}}/{\partial t^2} = 0 \qquad (14)$$

We can define L by

$$L \equiv \xi_{\mathrm{Re}} - i\sqrt{\frac{\mu}{\varepsilon}}\xi_{\mathrm{Im}} \qquad (15)$$

where $\phi_{\mathrm{Re}} = -\nabla \cdot \underline{\xi}$ and we can write such expressions as

$$A_{\mathrm{Im}} = \mu\varepsilon \frac{\partial \xi_{\mathrm{Im}}}{\partial t} \quad \text{and} \quad \phi_{\mathrm{Im}} = \nabla \cdot \underline{\xi}_{\mathrm{Im}} \qquad (16)$$

This formalism works for a dielectric media but if the media is conducting the field equations is no longer symmetric then the method fails. Symmetry is maintained by introducing a complex induced capacity $\varepsilon' = \varepsilon_{\text{Re}} \pm i(\sigma_{\text{Im}} / \omega)$. If the vector B is in a solenoid charge-free region then this method works. Calculation of states of polarization by the complex method demonstrates its usefulness and validity. Also, absorption can be considered in terms of complex fields. In the complex space, V may also contain non-Hertzian as well as Hertzian components, L. We will apply this method to solutions that can be described as retarded and advanced and may explain Bell's theorem and other nonlocal phenomena. Linear and circular polarization can be expressed in terms of complex vectors $A = A_{\text{Re}} + iA_{\text{Im}}$. The light quanta undergoing this polarization is given as, $\hbar\omega\hat{n} = \hbar\sigma = \hbar k$. Complex unit vectors are introduced so that real and imaginary components are considered orthogonal. We have a form such as $\underline{A} = (\underline{A} \cdot \hat{\ell}_{\text{Im}})\hat{\ell}_{\text{Re}} + (\underline{A} \cdot \hat{j}_{\text{Im}})\hat{j}_{\text{Re}}$. The linearly polarized wave at angle θ is

$$\underline{A} = \frac{A}{\sqrt{2}}(\hat{\ell}_{\text{Re}} \quad e^{-i\theta} - i\underline{j}_{\text{Re}} \quad e^{i\theta}). \tag{17}$$

Now let us consider use of this polarization formalism to describe the polarization-detection process in the calcium source photon experiment of Clauser et al [4], Aspect, et al [5] and Gisin, et al [6]. First we examine solutions to the field equations for time-like and space-like events. The non-locality of Bell's theorem appears to be related to the remote connectedness of the complex geometry and the stability of the soliton over space and time.

We will consider periodically varying fields which move along the x-axis later in this chapter. For source-free space, we can write

$$c^2 \nabla^2 \underline{F} = \varphi^2 \frac{F}{\varphi t^2} \tag{18}$$

where $\underline{F}$ represents either $\underline{E}$ or $\underline{B}$. The two independent solutions for this equation are [7]

$$\underline{E}_{\pm}(x,t) = E_0 \sin(2\pi kx \pm \nu t)$$

and

$$\underline{B}_{\pm}(x,t) = B_0 \sin\ 2\pi(kx \pm \nu t) \tag{19}$$

and k is the wave number and ν the frequency of the wave. The $\pm$ sign refers to the two independent solutions to the above second order equation in space and time. The wave corresponding to E_+ and B_+ will exist only when $t_0 < 0$ (past lightcone) and the wave corresponding to $\underline{E}$ and $\underline{B}$ will exist for $t_0 > 0$ (future lightcone) where t_0 is at the origin of the lightcone or the moment "now". Then the E_- wave arrives at a point x in a time t after emission, while E_+ wave arrive at x in time, t before emission (like a tachyonic signal).

2. Advanced and Retarded Solutions

Using Maxwell's equations for one spatial dimension, x, and the Poynting vector which indicates the direction of energy and momentum flow of the electromagnetic wave, we find that E_+ and B_+ correspond to a wave emitted in the +*x* direction but with energy flowing in the -*x* direction. For example, $E_+(x, t)$ is a negatives-energy and negative-frequency solution. The wave signal will arrive $t = x/c$ before it is emitted, and is termed an advanced wave. The solution $\underline{E}(x,t)$ is the normal positive-energy solution and arrives at *x* in time, $t = x/c$, after the instant of emission and is called the retarded potential, which is the usual potential.

The negative energy solutions can be interpreted in the quantum picture in quantum electrodynamics as virtual quantum states such as vacuum states in the Fermi-Dirac sea model [8] See Chap. 12. These virtual states are not fully realizable as a single real state but can definitely effect real physical processes to a significant testable extent [9]. The causality conditions in S-matrix theory, as expressed by analytic continuation in the complex plane, relate real and virtual states [10,11] and Chap. 4. Virtual states can operate as a polarizable media leading to modification of real physical states. In fact, coherent collective excitations of a real media can be explained through the operations in a underlying virtual media [9]. These virtual states in physical plasma operating through collective quantum electron states, effect the dielectric constant, conductivity and other electromagnetic properties of plasma which, experimentally differ from the classical properties and agree with theoretical quantum conditions which include the vacuum state [9,12].

Four solutions emerge: Two retarded (F_1 and F_2) connecting processes in the forward light cone and two advanced, (F_3 and F_4) connecting processes in the backward slight cone [13]. These four solutions are

$$\begin{aligned} F_1 &= F_0 e^{-i(-kx-\omega t)}, \quad F_2 = F_0 e^{i(kx-\omega t)}; \\ F_3 &= F_0 e^{i(-kx+\omega t)}, \quad F_4 = e^{i(kx+\omega t)} \end{aligned} \tag{20}$$

where F_1 is for a wave moving in the (-*x*, + *t*) direction, F_2 is for a (+x, +t) moving wave, F_3 is for a (-*x*, -*t*) moving wave, and F_4 is a (+*x*, -*t*) moving wave. F_1 and F_4 are complex conjugates of each other and F_2 and F_3, are complex conjugates of each other, so that $F_1^+ = F_4$ and $F_2^+ = F_3$; where the usual solutions to Maxwell's equations are then retarded plane wave solutions [3,13].

The proper formulation of nonlocal correlations, which appear to come out of complex geometries provides a conceptual framework for a number of quantum mechanical paradoxes and appear to be explained by Bell's nonlocality, Young's double slit experiment, the Schrödinger cat paradox, superconductivity, superfluidity, and plasma 'instabilities' or coherent collective states including Wheeler's 'delayed choice experiment'. (See Chap. 4) A paradox is caused by a lack of under-standing of a physical observation and is resolved by a new and better comprehension of the interpretation of the observation and/or new observation. Interpretation of these phenomena is made in terms of their implications about the lack of locality and the decomposition of the wave function which arises from the action of advanced waves which 'verify' the quantum mechanical transactions or communications. See Fig. 1.

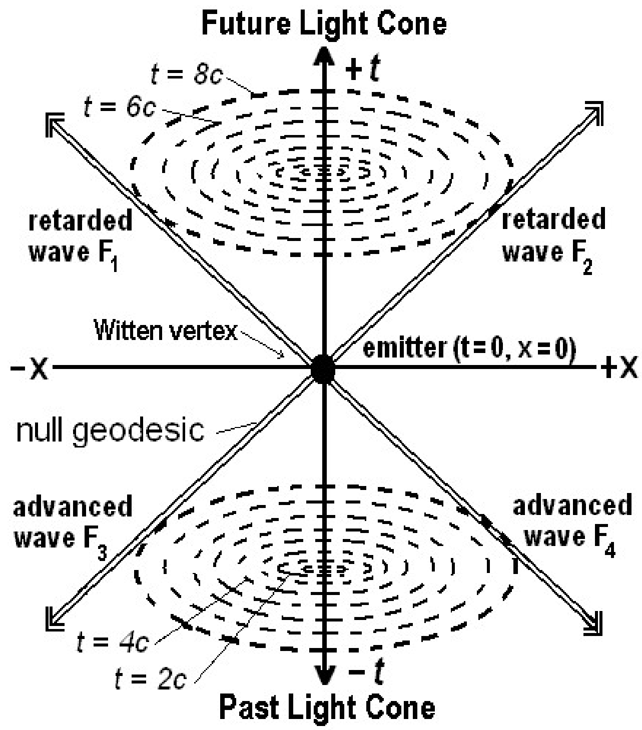

Figure 1 Adaptation of a complex Minkowski lightcone showing advanced-retarded future-past elements, F_1 – F_4, see Eq. (20), of a Cramer wavefront transaction with a central Witten model Ising lattice string vertex able to undergo continuous-state symmetry transformations of the Riemann sphere, $0 \leftrightarrow \infty$ rotation.

Cramer [13] demonstrated that the communication path between detectors in the Bell inequality experiments can be represented by space-like intervals that produce the quantum mechanical result by the addition of two time-like 4-vectors having time components of opposite signs, which demonstrate the locality violations of Bell's theorem; and are consistent with the Clauser, Fry, Aspect and Gisen experiments [4-6]. This model essentially is an 'action-at-a-distance' formalism [14].

One can think of the emitter (in Bell's or Young's experimental quantum condition) as sending out a pilot or probe 'wave' in various allowed directions to seek a 'transaction' or collapse of the wave function. A receiver or absorber detects or senses one of these probe waves, 'sets its state' and sends a 'verifying wave' back to the emitter confirming the transaction and arranging for the transfer of actual energy and momentum. This process comprises the nonlocal collapse of the wave function. De Broglie termed such a wave a pilot wave. The question becomes: does such a principle have macroscopic effects? The distance record for Bell's nonlocality theorem was 10km in 1997 [6], obtained by Nicolas Gisin and his team at the University of Geneva. Starting from a Geneva railway station they sent entangled photons along optical fibers through the city to destinations separated by 10km. They showed that observing the state of one member of the pair instantaneously determined the state of the other.

An attempt to examine such possible macroscopic effects over large distances has been made by Partridge [15]. Using 9.7GHz microwaves transmitted by a conical horn antenna so that waves were beamed in various directions. Partridge found that there was little evidence for decreased emission intensities in any direction for an accuracy of a few parts per 10^{9th} . Interpretation of such a process is made in terms of advanced potentials. Previously mentioned complex dimensional geometries give rise to solutions of equations forming subluminal and superluminal signal propagations or solitons. See Chaps. 9 and 10.

The possibility of a remote transmitter-absorber communicator now appears to be a possibility. The key to this end is an experiment by Pflelgov and Mandel [16]. Interference effects have been demonstrated, according to the authors, in the superposition of two light beams from two independent lasers. Intensity is kept so low that, to high probability, one photon is absorbed before the next is emitted. The analogy to Young's double slit experiment is enormous.

In Wheeler's work [17-19], he presents a detailed discussion of the physics of delayed choice photon interference and the double slit experiment (based on the Solvay conference Bohr-Einstein dialogue). Wheeler discusses the so-called Bohm ‘hidden variables’ as a possible determinant that nonlocality collapses the wave function [17]. Remote wave functions once entangled remain entangled over space-like separation, i.e. provide a possible solution to the Schrödinger cat paradox. Further theoretical and experimental investigation is indicated; but there appears to be a vast potential for remote non-local communication and perhaps even energy transfer [3]. In Chap. 9 we detail the forms of transformations of the vector and scalar potentials at rest and in moving frames, continuing our formulation in terms of $(\underline{A},\phi)$. The issues of sub and superluminal transformations of $\underline{A}$ and ϕ are given in a complex Minkowski space. Both damped and oscillatory solutions are found and conditions for advanced and restored potentials are given.

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