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AHARONOV-BOHM EFFECT AS THE BASIS OF ELECTROMAGNETIC ENERGY INHERENT IN THE VACUUM

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The Aharonov-Bohm effect shows that the vacuum is structured, and that there can exist a finite vector potential **A** in the vacuum when the electric field strength **E** and magnetic flux density **B** are zero. It is shown on this basis that gauge theory produces energy inherent in the vacuum. The latter is considered as the internal space of the gauge theory, containing a field made up of components of **A**, to which a local gauge transformation is applied to produce the electromagnetic field tensor, a vacuum charge/current density, and a topological charge g. Local gauge transformation is the result of special relativity and introduces spacetime curvature, which gives rise to an electromagnetic field whose source is a vacuum charge current density made up of **A** and g. The field carries energy to a device which can in principle extract energy from the vacuum. The development is given for $U(1)$ and $O(3)$ invariant gauge theory applied to electrodynamics.

Key words: Aharonov-Bohm effect, energy from the vacuum, $U(1)$ and $O(3)$ invariant gauge theory applied to electrodynamics.

1. INTRODUCTION

The Aharonov-Bohm effect shows that the classical vacuum is configured or structured, and that the configuration can be described by gauge theory [1-3]. The result of this experiment is that in the structured vacuum, the vector potential **A** can be non-zero while the electric field strength **E** and magnetic flux density **B** can be zero. This result is developed in Sec. 2 by defining an inner space for the gauge theory consisting of components of the vector potential **A**, components which obey the d'Alembert wave equation. A local gauge transformation is applied in Sec. 2 to the Lagrangian describing this vacuum, a gauge transformation which produces a topological charge g, defined as part of a covariant derivative, and a vacuum charge current density which acts as the source for an electromagnetic field propagating in the vacuum. The latter carries electromagnetic energy/momentum, which is therefore inherent in the vacuum because local gauge transformation uses covariant derivatives, meaning that axes vary from point to point and that there is spacetime curvature. The latter is the source of the electromagnetic energy/momentum inherent in the vacuum. There is no theoretical upper bound to the magnitude of this electromagnetic energy/momentum, which can be picked up by receivers in the usual way. Therefore devices can be manufactured in principle to take an unlimited amount of electromagnetic energy from the vacuum as defined by the Aharonov-Bohm effect, without violating Noethers Theorem.

The gauge theory is developed for two types of non-simply connected vacua, described respectively by the $(U)1$ and $(O)3$ gauge groups. It has been well established recently that an $O(3)$ invariant electrodynamics has several major advantages over the received $U(1)$ invariant electrodynamics [1-3]. However, the use of the $U(1)$ invariant theory illustrates the method and produces the key results. Thereafter the technically more formidable $O(3)$ invariant theory is developed to give the same overall result, that electromagnetic energy is inherent in the structured vacuum, and there exists therein a Poynting Theorem, a form of the Noether Theorem. The theory being used is standard gauge field theory, so the Noether Theorem is conserved. The laws of conservation of energy/momentum and charge/current density are conserved. The magnitude of the energy/momentum is not bounded above by gauge theory, so the Poynting Theorem (law of conservation of electromagnetic energy) in the structured vacuum indicates this fact through the presence of a constant of integration whose magnitude is not bounded above. This suggests that the magnitude of the electromagnetic energy inherent in the structured classical vacuum is in effect limitless.

2. DEFINITION OF THE STRUCTURED VACUUM

The non-simply connected [1-3] $U(1)$ vacuum is considered firstly in order to illustrate the method as simply as possible. This vacuum is defined by the globally invariant Lagrangian density,

$$\mathcal{L} = \partial_\mu A \partial^\mu A^*, \tag{1}$$

where $\mathbf{A}$ and $\mathbf{A}^*$ are considered to be independent complex scalar components. They are complex because they are associated [4-25] with a topological charge g, which appears in the covariant derivative when the Lagrangian (Eq. 1) is subjected to local gauge transformation. The topological charge g should not be confused with the point charge e on the proton. In the classical structured vacuum g exists but e does not exist. The two scalar fields are therefore defined as complex conjugates:

$$A = (1/\sqrt{2})(A_1 + iA_2), \tag{2}$$

$$A^* = (1/\sqrt{2})(A_1 - iA_2). \tag{3}$$

The two independent Euler-Lagrange equations

$$\frac{\partial \mathcal{L}}{\partial \mathcal{A}} = \partial_\nu \left(\frac{\partial \mathcal{L}}{\partial(\partial_\mu \mathcal{A})} \right), \quad \frac{\partial \mathcal{L}}{\partial \mathcal{A}^*} = \partial_\nu \left(\frac{\partial \mathcal{L}}{\partial(\partial_\mu \mathcal{A}^*)} \right) \tag{4}$$

produce the independent d'Alembert equations of the structured vacuum:

$$\Delta A = 0, \quad \Delta A^* = 0, \tag{5}$$

where $\Delta := \nabla^2 - (1/c^2)\partial^2/\partial t^2$. The Lagrangian is invariant under a global gauge transformation

$$A \to e^{-i\Lambda}A, \quad A^* \to e^{i\Lambda}A^*, \tag{6}$$

where A is a number. Under a local gauge transformation, however,

$$A \to e^{-i\Lambda(x)}A, \quad A^* \to e^{i\Lambda(x)}A^*, \tag{7}$$

where A becomes [1-3] a function of the spacetime coordinate x^μ. Under the local gauge transformation [7] of the structured $U(1)$ vacuum defined by the Lagrangian [1], the latter is changed [1,25] to

$$\mathcal{L} = \mathcal{D}_\mu A \mathcal{D}^\mu A - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}. \tag{8}$$

Here $F_{\mu\nu}$ is the $U(1)$ invariant electromagnetic field tensor, defined by

$$F_{\mu\nu} := \partial_\mu A_\nu - \partial_\nu A_\mu, \tag{9}$$

where the covariant derivatives [1-3] are given by

$$\mathcal{D}_\mu A := (\partial_\mu + igA_\mu)A, \tag{10}$$

$$\mathcal{D}_\mu A^* := (\partial_\mu - igA_\mu)A^*. \tag{11}$$

Here A_μ is the vector four-potential in spacetime. The topological charge g has the units

$$g = \kappa/A^{(0)}, \tag{12}$$

where κ is the wave-vector magnitude of the electromagnetic field and A^0 denotes the scalar magnitude of A. We therefore obtain

$$gA_\mu = \kappa_\mu, \tag{13}$$

where κ_μ is energy momentum. This result illustrates the fact that the covariant derivative measures the way in which coordinates vary from point to point in spacetime in gauge theory [1-3]. Such a variation in fact produces curvature and energy-momentum, in this case energy-momenta which is carried by the electromagnetic field. The latter is the result of the invariance of the Lagrangian (1) of the structured $U(1)$ vacuum under a local gauge transformation.

By using the Euler-Lagrange equation

$$\partial_\nu \left(\frac{\partial \mathcal{L}}{\partial(\partial_\nu A_\mu)} \right) = \frac{\partial \mathcal{L}}{\partial A_\mu} \tag{14}$$

and the Lagrangian (8), we obtain the field quation of the $U(1)$ structured vacuum:

$$\partial_\nu F^{\mu\nu} = -icg(A^*\mathcal{D}^\mu A - A\mathcal{D}^\mu A^*), \tag{15}$$

a field equation that identifies the vacuum charge current density

$$J^\mu(\text{vac}) = -icg\epsilon_0(A^*\mathcal{D}^\mu A - A\mathcal{D}^\mu A^*), \tag{16}$$

first introduced by Lehnert [4-6] and developed by Lehnert and Roy [7]. These authors have provided empirical evidence for the existence of the current [16] and have shown that its existence implies a finite photon mass [7]. Furthermore, a loop integration $\oint J^\mu(\text{vac})dx_\mu$ will in general be nonzero, and it defines the Aharonov-Bohm phase induced by the gauge vector field.

Equation (15) is an inhomogeneous field equation from which can be constructed a Poynting Theorem for the $U(1)$ structured vacuum using standard methods. The latter are based on the existence of the charge current density $J^\mu(\text{vac})$ in Eq. (15), generating the energy

$$E = \int J^\mu(\text{vac})A_\mu dV, \tag{17}$$

and the power

$$\frac{dW}{dt} = \int J^\mu E_\mu dV. \tag{18}$$

The volume V is arbitrary, and standard methods [3] give the Poynting theorem of the $U(1)$ structured vacuum:

$$\frac{dU}{dt}(\text{vac}) + \nabla\cdot\mathbf{S}(\text{vac}) = -\mathbf{J}(\text{vac})\cdot\mathbf{E}. \tag{19}$$

Here $\mathbf{S}(\text{vac})$ is the Poynting vector of the $U(1)$ structured vacuum that represents electromagnetic energy flow and is defined by

$$\nabla\cdot\mathbf{S}(\text{vac}) = -\mathbf{J}(\text{vac})\cdot\mathbf{E}. \tag{20}$$

Integration of this equation gives

$$S(\text{vac}) = -\int \mathbf{J}(\text{vac})\cdot\mathbf{E}d\sigma + \text{const.}, \tag{21}$$

where the constant of integration is not bounded above. The electromagnetic energy flow inherent in the $U(1)$ structured vacuum is not bounded above, meaning that there is an unlimited amount of electromagnetic energy flow available in theory for use by devices. Some of these devices are reviewed in Ref. [23]. Sometimes, the constant of integration is referred to as the Heaviside component of the vacuum electromagnetic energy flow, and the detailed nature of this component is not restricted in any way by gauge theory. The Poynting theorem [19] is of course the result of gauge theory.

3. NON-SIMPLY CONNECTED O(3) VACUUM

In the non-simply connected $O(3)$ vacuum the internal gauge space is a vector space rather than the scalar space of the $U(1)$ vacuum. Therefore there exist the independent complex vectors $\mathbf{A}$ and $\mathbf{A}^*$ in this physical internal gauge space. The globally invariant Lagrangian for the internal space is

$$\mathcal{L} = \partial_\mu \mathbf{A} \partial^\mu \mathbf{A}^*, \tag{22}$$

and the two independent Euler-Lagrange equations are

$$\partial_\nu \left(\frac{\partial \mathcal{L}}{\partial(\partial_\mu A_\mu)} \right) = \frac{\partial \mathcal{L}}{\partial A_\mu}, \quad \partial_\nu \left(\frac{\partial \mathcal{L}}{\partial(\partial_\mu A_\mu^*)} \right) = \frac{\partial \mathcal{L}}{\partial A_\mu^*}, \tag{23}$$

giving the d'Alembert equations

$$\Delta A = 0, \quad \Delta A^* = 0. \tag{24}$$

Under the local $O(3)$ invariant gauge transformation

$$A \to e^{-i\Lambda} A, \quad A^* \to e^{i\Lambda} A^*, \tag{25}$$

the Lagrangian (22) becomes

$$\mathcal{L} = \mathcal{D}_\mu A \mathcal{D}^\mu A - \frac{1}{4} G_{\mu\nu} G^{\mu\nu}. \tag{26}$$

And, using the Euler-Lagrange equation

$$\partial_\nu \left(\frac{\partial \mathcal{L}}{\partial(\partial_\mu A_\mu)} \right) = \frac{\partial \mathcal{L}}{\partial A_\mu}, \tag{27}$$

the inhomogeneous $O(3)$ invariant field equation is retrieved:

$$\mathcal{D}_\nu G^{\mu\nu} = -g \mathcal{D}^\mu \mathbf{A}^* \times \mathbf{A}. \tag{28}$$

The term on the right-hand side is the $O(3)$ invariant vacuum charge current density that is the non-Abelian equivalent of the right-hand side of Eq. (15). In general Eq. (28) must be solved numerically, but the presence of a vacuum charge current density gives rise to the vacuum energy

$$E(\text{vac}) = \int J^\mu(\text{vac}) A_\mu dV, \tag{29}$$

whose source is curvature of spacetime introduced by the $O(3)$ covariant derivative (1-25) which contains the rotation generator J of $O(3)$. The curvature of spacetime is also the source of photon mass, in analogy with general relativity, where curvature of spacetime occurs in the presence of mass or a gravitating object.

4. DISCUSSION

The empirical basis of the development in Secs. 2 and 3 is that the Aharonov-Bohm effect shows that in regions where **E** and **B** are both zero, **A** can be non-zero. Therefore the Aharonov Bohm effect can be thought of [1-3] as a local gauge transformation of the pure vacuum, defined by $A_\mu = 0$, and the effect shows that a non-zero A_μ can be generated by gauge transformation from regions where A_μ is zero. Therefore in a structured vacuum it is possible to construct a gauge theory whose internal space is defined by non-zero components of A_μ in the absence of an electromagnetic field. The latter is generated by a local gauge transformation which was generated originally by a local gauge transformation of the pure vacuum defined by $A_\mu = 0$. This concept is true for all gauge group symmetries. It is well known that contemporary gauge theories lead to richly structured vacua whose properties are determined by topology [1-25]. The Yang-Mills vacuum discussed in Sec. 3 is infinitely degenerate. Therefore local gauge transformation can produce electromagnetic energy, a vacuum charge current density, a vacuum Poynting theorem and photon mass, all inter-related concepts. We reach the sensible conclusion that in the presence of a gravitating object (a photon with mass), spacetime is curved. The curvature is described through the covariant derivative for all gauge group symmetries. The energy inherent in the vacuum is contained in the electromagnetic field and the coefficient g is a topological charge inherent in the vacuum. For all gauge symmetries the product gA is within a factor energy/momentum, indicating clearly that the covariant derivative applied in the vacuum contains energy-momentum produced on the classical level by spacetime curvature. This energy-momentum, as in general relativity, is not bounded above, so the electromagnetic energy inherent in the classical structured vacuum is not bounded above. There appear to be several devices (23) available which extract this vacuum electromagnetic energy, which is in principle unlimited.

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