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

by

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ABSTRACT

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. 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 space-time 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 a U(1) and O(3) invariant gauge theory applied to electrodynamics.

KEYWORDS: 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 ~~this~~ section 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 section 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 space-time 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 Noether's 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 {4-25} 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 { I-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:

$$\mathcal{L} = \partial_\mu A \, \partial^\mu A^* \qquad -(1)$$

where A and $A^*$ 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** ( $\mathcal{L}$ ) 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:

$$A = \frac{1}{\sqrt{2}} (A_1 + i A_2) \qquad -(2)$$

$$A^* = \frac{1}{\sqrt{2}} (A_1 - i A_2) \qquad -(3)$$

The two independent Euler Lagrange equations:

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

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

$$\square A = 0 ; \quad \square A^* = 0 . \quad -(5)$$

The lagrangian ( 1 ) is invariant under a global gauge transformation:

$$A \rightarrow e^{-i\Lambda} A ; \quad A^* \rightarrow e^{i\Lambda} A^* \quad -(6)$$

where $\Lambda$ is a number. Under a local gauge transformation however:

$$A \rightarrow e^{-i\Lambda(x^\mu)} A ; \quad A^* \rightarrow e^{i\Lambda(x^\mu)} A^* \quad -(7)$$

where $\Lambda$ becomes {1 - 3} a function of the space-time coordinate $x^\mu$ by special relativity. Under the local gauge transformation ( 7 ) of the structured U(1) vacuum defined by the lagrangian ( 1 ) the latter is changed { 1, 25} to:

$$\mathcal{L} = D_\mu A D^\mu A^* - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} \quad -(8)$$

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

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \qquad -(9)$$

and where the **covariant** derivatives {1 – 3} **are** defined by:

$$D_\mu A = (\partial_\mu + ig A_\mu) A \qquad -(10)$$

$$D^\mu A^* = (\partial^\mu - ig A^\mu) A^*. \qquad -(11)$$

Here $A_\mu$ is the vector four potential in space-time. **The** topological charge **g** has the units:

$$g = \frac{\kappa}{A^{(0)}} \qquad -(12)$$

where $\kappa$ is the wave-vector magnitude of the electromagnetic field and where $A^{(0)}$ is the scalar magnitude of $A_\mu$. Therefore we **obtain:**

$$g A_\mu = \kappa_\mu \qquad -(13)$$

where $\kappa_\mu$ is energy momentum within a **factor $\hbar$** { a s }. **This result** illustrates the fact that the covariant derivative measures the way in which coordinates **vary from point to point in space-time in gauge theory {1 – 3}.** Such a variation **introduces** curvature and energy-momentum, in this case energy-momentum 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:

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

with the lagrangian ( 8 ) we obtain the field equation of the U(1) structured vacuum:

$$\partial_\nu F^{\mu\nu} = -igc\left(A^* D^\mu A - A D^\mu A^*\right), \quad - (15)$$

a field equation which identifies the vacuum charge current density:

$$J^\mu(vac) := -igc\epsilon_0\left(A^* D^\mu A - A D^\mu A^*\right) \quad - (16)$$

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 that of finite photon mass { 7 }.

**Eqn.** ( 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 $J^{\mu}(vac)$ in **eqn.** ( 15 ), generating the energy:

$$En = \int J^{\mu}(vac) A_{\mu} \, dV \quad -(17)$$

and rate of doing work:

$$\frac{d\bar{W}}{dt} = \int \underline{J}(vac) \cdot \underline{E} \, dV. \quad -(18)$$

The volume V is arbitrary, and standard methods { 3 } give the Poynting Theorem of the U(1) structured vacuum:

$$\frac{\partial \bar{U}(vac)}{\partial t} + \underline{\nabla} \cdot \underline{S}(vac) = -\underline{J}(vac) \cdot \underline{E}. \quad -(19)$$

Here $S(vac)$ is the Poynting vector of the U(1) **structured** vacuum, representing electromagnetic energy flow, and is defined by:

$$\underline{\nabla} \cdot \underline{S}(vac) = -\underline{J}(vac) \cdot \underline{E} \quad -(20)$$

Integrating this equation gives

$$\underline{S}(\text{vac}) = -\int \underline{J}(\text{vac}) \cdot \underline{E}\, dr + \text{constant of integration} \quad \text{—} (21)$$

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.~~

## 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 $\underline{A}$ aud $\underline{A}^*$ in this physical internal gauge space. The** globally invariant lagrangian for the **internal space is:**

$$\mathcal{L} = \partial_\mu \underline{A} \cdot \partial^\mu \underline{A}^* \qquad -(22)$$

and the two independent **Euler-Lagrange equations are:**

$$\frac{\partial \mathcal{L}}{\partial \underline{A}} = \partial_\nu \left( \frac{\partial \mathcal{L}}{\partial_\nu \underline{A}} \right) ; \quad \frac{\partial \mathcal{L}}{\partial \underline{A}^*} = \partial_\nu \left( \frac{\partial \mathcal{L}}{\partial_\nu \underline{A}^*} \right) \qquad -(23)$$

giving the **d'Alembert** equations:

$$\Box \underline{A} = \underline{0} \ ; \quad \Box \underline{A}^* = \underline{0} . \qquad -(24)$$

Under the local O(3) invariant gauge transformation:

$$\underline{A} \rightarrow e^{iJ_i\Lambda_i} \underline{A} \ ; \quad \underline{A}^* \rightarrow e^{-iJ_i\Lambda_i} \underline{A}^* \qquad -(25)$$

**the lagrangian (22) becomes:**

$$\mathcal{L} = D_\mu \underline{A} \cdot D^\mu \underline{A}^* - \frac{1}{4} \underline{G}_{\mu\nu} \cdot \underline{G}^{\mu\nu} \qquad (26)$$

**and using the** Euler-Lagrange equation:

$$\frac{\partial \mathcal{L}}{\partial \underline{A}_\mu} = \partial_\nu \left( \frac{\partial \mathcal{L}}{\partial(\partial_\nu \underline{A}_\mu)} \right) \qquad (27)$$

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

$$D_\nu \underline{G}^{\mu\nu} = -g D^\mu \underline{A}^* \times \underline{A}. \qquad (28)$$

**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 **eqn. ( 15 ). In general eqn. ( 28 ) must be solved numerically, but the presence of a vacuum charge current** density gives rise to the vacuum **energy:**

$$En(vac) = \int \underline{J}^\mu(vac) \cdot \underline{A}_\mu \, d\bar{V} \qquad (29)$$

**whose** source is **curvature of space-time introduced by the O(3) covariant derivative { 4 - 25} which contains the rotation generators** $(J_i)$ **of O(3). The curvature** of space-time is also the source of **photon mass, in analogy with general** relativity, where curvature of space-time occurs in the **presence of** mass or a gravitating object.

DISCUSSION

The empirical basis of the development in sections 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 $A^\mu$ can be generated by a local gauge transformation **from** regions where $A^\mu$ is zero. Therefore in a structured vacuum it is possible to construct a gauge theory whose internal space is defined by components of $A^\mu$ in the absence of an electromagnetic field. The latter is generated by a local gauge transformation of components of $A^\mu$ 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 section 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), space-time 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 group symmetries the product $gA^{\mu}$ is within a factor $\hbar$ energy / momentum, indicating clearly that the **covariant** derivative applied in the vacuum contains energy-momentum produced on the classical level by space-time 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.

~~**ACKNOWLEDGMENTS**~~

## ACKNOWLEDGMENTS

Funding for individual member laboratories of **AIAS** is acknowledged and support **from** the U.S. Department of Energy is acknowledged in the form of **website:**

**http://www.ott.doe.gov/electromagnetic/**

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