

Substratum Interpretation of the Sagnac- and the Aharonov-Bohm Effect

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It is shown that a substratum interpretation reveals a close relationship between the Sagnac- and the Aharonov-Bohm-effect. The characteristic peculiarity of the Aharonov-Bohm-effect, to produce a phase shift of the electron wave function even in the absence of any electromagnetic force fields, can be duplicated by a thought experiment for light waves in the gravitational field of a massive rotating cylinder, which demonstrates that the somewhat similar Sagnac-effect is not caused by centrifugal and Coriolis forces, as it is sometimes claimed.

In the substratum interpretation, both the Sagnac and Aharonov-Bohm effect find their explanation in a rotational motion of the substratum. If the substratum flow is irrotational, having the form of a potential vortex, these effects persist even though there are no force fields present.

1. Introduction

The outcome of his rotating interferometer experiment was used by Sagnac as a decisive argument against Einstein's claim that physics could do without the ether hypothesis [1]. Most of the text-books treating the Sagnac effect, like the well-known theoretical physics course by Sommerfeld [2], explain the effect by Sagnac's original argument, that it is caused by a whirling of the ether to be felt in a rotating reference system, but it is also often stated that the effect must somehow be caused by the centrifugal- and Coriolis-forces and for this reason should be treated in the framework of general relativity. A discussion of the Sagnac effect within general relativity can be found in the theoretical physics lectures by Landau and Lifshitz [3], where it is alleged that the effect is caused by the special stationary gravitational field which is set up in a rotating reference frame. However, already Ives [4], had given convincing arguments that the effect has nothing to do with the inertial forces in a rotating reference frame, keeping Sagnac's original argument to be valid as ever.

The interpretation of the Sagnac effect, which says that it is caused by an ether wind in the rotating reference system, would make in this system the velocity of light anisotropic. Such a conclusion seems to

contradict the outcome of the Michelson-Morley and other related experiments which claim to have proved the constancy of the velocity of light, and which gave Einstein the reason to discard the ether hypothesis. A close examination of all these experiments, however, shows that in reality one there never measures the one-way velocity of light, but rather always the to and fro velocity. This fact even finds its mathematical expression in the Lorentz transformations into which only c^2 , but not the vector c enters. As it was already known by Lorentz and Poincaré, the Lorentz transformations can also be interpreted dynamically, to result from true physical deformations of bodies in motion through an ether, instead of the kinematical interpretation by Einstein and Minkowski, explaining the transformations as the result of a pseudo-euclidean space-time symmetry [5]. In the dynamic interpretation, of the Lorentz transformations, the velocity of light in a reference system in motion against the substratum is in reality highly anisotropic, but because all measuring devices are deformed, this anisotropy cannot be detected. As a result, one can always only measure the trace $c^i c_i$ of the direction-dependent propagation tensor $c_i c_k$. Sagnac's interpretation is for this reason not subject to any logical contradiction if the alternative dynamic interpretation of special relativity is adopted.

A quite different effect where a phase shift on an electron wave occurs in the absence of any electromagnetic forces has been described by Aharonov and Bohm [6]. There, a change in the magnetic vector

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potential alone can produce a shift. The effect is explained as a direct consequence of Schrödinger's wave equation, into which the potentials and not the force fields enter. For this reason a case was made by Aharonov and Bohm to give the potentials a more direct physical meaning rather than to be just a convenient mathematical tool. However, to elevate the potentials to true physical significance has the problem that these potentials can always be changed by a gauge transformation without affecting the physical results derived from them. Because the potentials can measurably influence the phase of an electron wave in the absence of any electromagnetic force fields, it has alternatively been claimed that the effect is rather a proof for action at a distance at work in quantum mechanics, whereby the magnetic force field located inside the solenoid can influence the phase of the electron wave in the force-free region outside the solenoid.

We will show here that both the Sagnac and the Aharonov-Bohm effect can be understood to result from a rotational ether motion, revealing a close relationship between these effects. This picture not only gives a full physical explanation of the potentials and the meaning of a gauge transformation but also eliminates the need for any hypothetical action at a distance.

2. The Sagnac Effect

To analyze the Sagnac effect we take the somewhat simplified configuration shown in Figure 1. A light beam coming from the left is projected at position A onto a rotating table. At A the beam is split into two separate beams, each one following a half circle of radius r along the periphery of the table. At point B, both beams are again joined together and brought to interference. One of the two beams is propagating in the same direction as the velocity of the rotating table, the other one in the opposite direction. The rotating

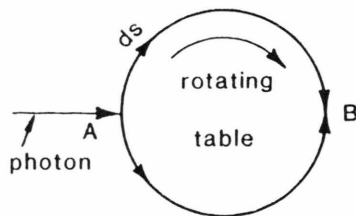


Fig. 1. Sagnac effect.

table shall have the angular velocity $-\Omega$, making its velocity at the radius r equal to $u = -r\Omega$.

According to the hypothesis of an ether at rest in the unaccelerated laboratory*, the velocity of light judged from a corotating reference system would be $c - v$ for the beam propagating in the same direction as the rotating table and $c + v$ for the beam propagating in the opposite direction, where $v = -u$ is the ether velocity in the rotating reference system. The time difference for both beams arriving at position B follows from

$$c \delta t = \oint_A^B (c + v) dt - \oint_A^B (c - v) dt \quad (1)$$

hence

$$\delta t = (1/c) \oint v dt. \quad (2)$$

If we are only interested in first order effects in v/c , we can put $dt \simeq (1/c) ds$, where ds is the line element along the circular path. If the light propagates along an arbitrary but simply connected curve we then have

$$\delta t = (1/c^2) \oint \mathbf{v} \cdot d\mathbf{s} \quad (3)$$

for which we can also write

$$\delta t = (1/c^2) \int \text{curl } \mathbf{v} \cdot d\mathbf{f}, \quad (4)$$

where $F = |\int d\mathbf{f}|$ is the surface enclosed by the light path. Because $\Omega = (1/2)|\text{curl } \mathbf{v}|$ we find

$$\delta t = 2\Omega F/c^2, \quad (5)$$

which agrees with the result obtained by Sagnac.

For the phase shift $\delta\varphi = \omega \delta t$, where ω is the circular frequency of the wave, we have

$$\delta\varphi = (\omega/c^2) \oint \mathbf{v} \cdot d\mathbf{s}. \quad (6)$$

3. The Aharonov-Bohm Effect

The arrangement for the observation of this effect is shown in Figure 2. An electron beam coming from the left is split at point A into two separate beams, to be brought together again at point B and where they interfere. In their separate paths they bypass an infinitely long magnetic solenoid. Even though there can be no magnetic field outside the solenoid, a direct application of Schrödinger's wave equation yields at

* The reasoning would be unchanged if the laboratory would move with a constant velocity against the ether.

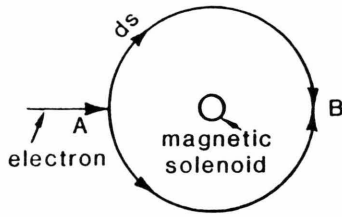


Fig. 2. Aharonov-Bohm effect.

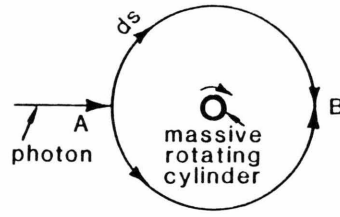


Fig. 3. Gravitational-Aharonov-Bohm effect.

point B a phase shift which is

$$\begin{aligned}\delta\varphi &= -\frac{e}{\hbar c} \left[\oint_A^B \mathbf{A} \cdot d\mathbf{s} - \oint_A^B \mathbf{A} \cdot d\mathbf{s} \right] \\ &= -\frac{e}{\hbar c} \oint \mathbf{A} \cdot d\mathbf{s}.\end{aligned}\quad (7)$$

With $\mathbf{H} = \text{curl } \mathbf{A}$ we can write for (7)

$$\begin{aligned}\delta\varphi &= -\frac{e}{\hbar c} \int \text{curl } \mathbf{A} \cdot d\mathbf{f} = -\frac{e}{\hbar c} \int \mathbf{H} \cdot d\mathbf{f} \\ &= -\frac{e}{\hbar c} \Phi,\end{aligned}\quad (8)$$

where Φ is the total magnetic flux enclosed within the electron paths.

4. Gravitational Aharonov-Bohm Effect

The similarity between (6) for the Sagnac effect and (7) for the Aharonov-Bohm effect is enhanced by identifying the substratum velocity \mathbf{v} in the Sagnac experiment with the gravitational vector potential \mathbf{A} , which is [7].

$$\mathbf{A} = -(c/4) \mathbf{v} \quad (9)$$

with $\text{div } \mathbf{A} = \text{div } \mathbf{v} = 0$. This brings (6) for the Sagnac effect into the form

$$\delta\varphi = -4(\omega/c^3) \oint \mathbf{A} \cdot d\mathbf{s}. \quad (10)$$

Applied to a single photon with a mass $m = \hbar \omega/c^2$, (10) becomes

$$\delta\varphi = -4 \frac{m}{\hbar c} \oint \mathbf{A} \cdot d\mathbf{s}. \quad (11)$$

In this form it is very similar to (7), except that the shift is 4 times larger and that e has been replaced by m .

In spite of the similarity of (7) and (11), there remains the important difference: In (7) $\text{curl } \mathbf{A} = 0$

along the entire electron path, whereas, in (11) $\text{curl } \mathbf{A} = -(c/4) \text{curl } \mathbf{v} = -\Omega c/2 \neq 0$. This means that only the Aharonov-Bohm effect has a phase shift in the absence of a force field.

The described difference between the Sagnac and the Aharonov-Bohm effect does not occur in a gravitational Aharonov-Bohm effect, which works with photons and is for this reason very similar to the Sagnac effect. In it the magnetic solenoid is replaced by a massive rotating hollow cylinder.

The magnetic vector potential in the Aharonov-Bohm effect is determined by the equation

$$\nabla^2 \mathbf{A} = -\frac{4\pi}{c} \mathbf{j}, \quad (12)$$

where \mathbf{j} is the electric current density. Outside a solenoid of radius r_0 and current carrying layer of thickness δ one finds:

$$A_\varphi = (2\pi j r_0^2 \delta/c) (1/r), \quad (13)$$

for which $\text{curl } \mathbf{A} = 0$. Likewise, the gravitational vector potential is obtained from

$$\nabla^2 \mathbf{A} = \frac{4\pi G}{c} \varrho \mathbf{V}, \quad (14)$$

where ϱ is the density and \mathbf{V} the velocity of moving masses. G is Newton's constant. Equation (14) can be obtained from Einstein's linearized field equations, but it also follows from a previously proposed vector theory of gravity with substratum [7]. The curl of the gravitational vector potential produces a gravitational field resembling a magnetic field. Outside the rotating hollow cylinder of thickness δ one finds

$$A_\varphi = -(2\pi G \varrho V r_0^2 \delta/c) (1/r). \quad (15)$$

The phase shift for two photon beams going around the cylinder is still given by (11), but here one has $\text{curl } \mathbf{A} = 0$ and, therefore, no magnetic-type gravitational field in the space through which the light passes.

5. Ether Interpretation of the Aharonov-Bohm Effect

The ether interpretation of the Sagnac and the gravitational Aharonov-Bohm effect is now obvious: In both cases, the phase shift is caused by a swirling motion of the ether. The phase shift for a single photon of mass $m = \hbar \omega / c^2$ obtained from (6) is

$$\delta\varphi = (m/\hbar) \oint \mathbf{v} \cdot d\mathbf{s}. \quad (16)$$

Under the circumstances of the gravitational Aharonov-Bohm effect, a potential vortex is set up in the ether around the rotating cylindrical shell, with an angular velocity of the ether given by (15) and (9):

$$v_\varphi = \frac{8\pi G \varrho V r_0^2 \delta}{c^2} \frac{1}{r}. \quad (17)$$

In the Sagnac effect the ether instead rotates with constant angular velocity Ω , for which $\Omega = (1/2) \text{curl} \mathbf{v} \neq 0$, leading to the erroneous conclusion that the effect may somehow have its cause in the centrifugal- and Coriolis-forces. Equation (4) rather shows that for the Sagnac experiment the phase shift is proportional to the vorticity flux within the area enclosed by the light paths.

The quite simple substratum explanation of the Sagnac and gravitational Aharonov-Bohm effect raises the question, if the magnetic Aharonov-Bohm effect might perhaps as well result from a potential vortex in the ether. A partial answer to this question is supplied by the quantum mechanical expression for the current of the electron wave, giving a value for the electron velocity:

$$\mathbf{v} = -\frac{i\hbar}{2m\psi^*\psi} [\psi^* \nabla \psi - \psi \nabla \psi^*] - \frac{e}{mc} \mathbf{A}, \quad (18)$$

where ψ is the Schrödinger wave function for the electron and m the electron mass. The first term on the r.h.s. of (18) does not lead to the phase shift of the Aharonov-Bohm effect and, therefore, can in the following discussion be ignored. Equation (18) then reduces to

$$\mathbf{v} = -\frac{e}{mc} \mathbf{A}. \quad (19)$$

A comparison with (9) suggests that the magnetic vector potential produces a potential vortex dragging the electron along with it. According to (13), the velocity in this vortex is given by

$$v_\varphi = -\frac{e}{mc^2} \frac{2\pi j r_0^2 \delta}{r}. \quad (20)$$

Furthermore, expressing \mathbf{A} through \mathbf{v} by (19), (7) reads

$$\delta\varphi = (m/\hbar) \oint \mathbf{v} \cdot d\mathbf{s}, \quad (21)$$

which has now the same form as for the photon given by (16).

The interpretation for both the magnetic and gravitational Aharonov-Bohm effect, to be caused by a potential vortex in the ether, removes any hypothetical action at a distance. A change in the vector potential, by a change in the magnetic or gravitational field flux, would be radially propagated by an electromagnetic or gravitational wave at the speed of light, eliminating any faster than light signalling.

The explanation of the Aharonov-Bohm effect by a potential vortex in the ether also shows that it completely avoids the problem connected with the arbitrariness of the vector potential by a gauge transformation. Since the potential vortex is uniquely determined by the sources, the ambiguity in the potential is removed by the requirement that the vector potential shall be expressed solely by the sources in the integral form

$$\mathbf{A}(\mathbf{r}) = \frac{1}{c} \int \frac{\mathbf{j}(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|} d\mathbf{r}' \quad (22)$$

with a similar expression for the gravitational vector potential. If always expressed in terms of the sources, the vector potential can then assume a true physical meaning. The phase shifts are, nevertheless, always gauge invariant because $\oint \mathbf{A} \cdot d\mathbf{s}$ is gauge invariant. A gauge transformation of the vector potential, if given by (22), implies the addition of an arbitrary $\text{grad } f(\mathbf{r})$ term, which then simply means the addition of a vorticity-free velocity field proportional to $\text{grad } f(\mathbf{r})$ to the potential vortex.

Real force fields only occur if the substratum flow has a non-vanishing vorticity, with the vorticity a direct measure of the field strength. The centrifugal- and Coriolis force fields in the Sagnac experiment can, therefore, be seen as being caused by a nonvanishing ether vorticity in the rotating reference frame.

With the help of (19), (8) for the magnetic Aharonov-Bohm effect assumes the form

$$\delta\varphi = (m/\hbar) |\text{curl} \mathbf{v}| F. \quad (23)$$

Putting $2\Omega = |\text{curl} \mathbf{v}|$, (5) for the Sagnac effect has then exactly the same form. This shows that (5) and (8) have essentially the same substratum interpretation.

6. Further Remarks about the Ether Interpretation

If, as the substratum interpretation claims, the Aharonov-Bohm effect is caused by a potential vortex in the ether, the question arises why this vortex has no energy. In both the magnetic and gravitational Aharonov-Bohm effect, there are no force fields in the region of the hypothetical ether vortex, and there is, therefore, no magnetic or gravitational field energy. But if the vortex is somehow real, it should have a mass and hence kinetic energy. This is a very similar problem as the one posed by the zero point energy of the vacuum. According to special relativity, this zero point energy is divergent but paradoxically produces no gravitational field. To overcome this problem it is suggested that special relativity is a dynamic symmetry caused by an exactly nonrelativistic superfluid ether, composed of positive and negative Planck masses. Its total energy is then always zero, but its fluctuations can go up all the way to the Planck energy [5, 7]. It is, furthermore, suggested that the ether forms a lattice of small ring vortices, with the ring radius about equal the grand unified length scale, and with the vortex core radius equal the Planck length. A vortex lattice of this kind can transmit transverse waves having the same mathematical structure as the waves derived from Maxwell's equations. For the wave to propagate, the vortices must be coupled to each other, which is possible through compression waves moving with the velocity of light, with a wave length larger than the Planck length and smaller than the vortex ring radius [8].

A comparison of the Sagnac effect with the gravitational Aharonov-Bohm effect shows that the ether and the vortex lattice immersed in it must both participate in the motion of the potential vortex. In the gravitational Aharonov-Bohm effect, every part of the ether must for this reason participate in the flow of the potential vortex. Not so in the magnetic Aharonov-Bohm effect. There the vortex produces a phase shift on the electron wave but does not influence the propagation of light. In the proposed ether model electrons are a sort of excitons made up from the masses of the positive and negative mass vortices. Unlike a light wave, which is propagated through the compression waves coupling the vortex rings of the vortex lattice, the electron would be a slow moving exciton propagating through the vortex lattice. The electron velocity can, therefore, be influenced by a motion of the

vortex lattice alone if this lattice moves against the ether in which the lattice is immersed.

According to a theorem by Helmholtz a vortex will move at a constant velocity under the mutual influence of other vortices [9]. This requirement is satisfied in a lattice of positive and negative mass vortices. It is, therefore, suggested that the potential vortex in the magnetic Aharonov-Bohm effect consists of a potential vortex made up from only that component of the ether consisting of the tiny positive and negative mass vortex rings.

Finally, we would like to make a few remarks on the meaning of the electrostatic potential V . Like the vector potential A it is arbitrary up to a gauge transformation which there amounts to the addition of an arbitrary function of time. As it was pointed out by Aharonov and Bohm [6], a time dependent electrostatic potential can likewise even in the absence of an electric field produce a phase shift experienced by an electron wave. The shift is there given by the gauge invariant expression

$$\delta\varphi = (e/h) \oint V dt. \quad (24)$$

The vector potential was explained as a substratum flow. A physical interpretation of the scalar potential can be obtained from the vector potential by a Lorentz transformation to a system at rest in this substratum flow. In this system (for $v^2/c^2 \ll 1$) there will be an electric potential which is

$$V' = -\mathbf{v} \cdot \mathbf{A}/c = (m/e) v^2 = (2 m c^2/e) \delta l/l, \quad (25)$$

where we have expressed A through v by (19), and where $\delta l/l \simeq (1/2) v^2/c^2$ is the Lorentz-contraction factor. For the gravitational potential we obtain in a similar way, expressing A through v by (9):

$$V' = -\mathbf{v} \cdot \mathbf{A}/c = v^2/4 = (c^2/2) \delta l/l, \quad (26)$$

In the new reference system, both the positive and negative masses are at rest but have both changed their density through a Lorentz contraction. With a change in the electric potential, therefore, goes along a change in the vortex density, and with a change in the gravitational potential a change in the density of the entire positive and negative mass substratum. The scalar potentials are, therefore, interpreted as different substratum densities. A change in the substratum density though does not affect the balance of the positive and negative masses and hence energy, the former in any case canceling out against each other.

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