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Absence of the Electric Aharonov-Bohm Effect due to Induced Charges

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This paper states that the induced charge should not be neglected in the electric Aharonov-Bohm (A-B) effect. If the induced charge is taken into account, the interference pattern of the moving charge will not change with the potential difference between the two metal tubes. It means that the scalar potential itself can not affect the phase of the moving charge, and the true factor affecting the phase of the moving charge is the energy of the system including the moving charge and the induced charge.

In classical physics, the concept of "force" is the most important, all the phenomena can be explained by the forces acting on the objects. In classical electrodynamics, the Lorentz force acting on a charge is determined by the electric field **E** and the magnetic field **B** at the position of the charge. So, the electric field **E** and the magnetic field **B** are considered as more fundamental quantities than the scalar potential φ and the vector potential **A**. But, in quantum mechanics, what appear in the Schrödinger equation are the scalar potential φ and the vector potential **A** instead of **E** and **B**. So, some physicists asserted that the potential functions φ and **A** are more fundamental than **E** and **B**[1]. Just for this reason, Y. Aharonov and D. Bohm predicted a new effect named by their names later[2]. This new effect asserts that the phase of a moving charge will be changed by the potential functions φ and **A**, even though the charge always move in a region where both **E** and **B** are zero, but the φ and **A** are not zero. This effect includes the electric A-B effect and the magnetic A-B effect. The magnetic A-B effect has been studied extensively in both theory and experiments[3–12]. The existence of the magnetic A-B effect has been supported by some experiments[3,5]. The theoretical and experimental studies on the magnetic A-B effect before 1989 have been well reviewed in the Ref. 8. But the electric A-B effect was much less studied[13–18]. Some experiments[13–16] attempted to observe the electric A-B effect, but none of them could completely avoid the classical force acting on the moving charge due to the magnetic or electric fields in the experiment. The quantitative experimental result about the influence of scale potential has not been reported. Recently, a new experimental method[18] has been advised, in which the moving electron is replaced by the moving hydrogen ion in order to lower the speed of the moving charge.

This paper will focus on the electric A-B effect in theory, especially, the possible experiment with two metal tubes proposed in the seminal paper by Aharonov and Bohm. It is found that a very important factor was neglected in their paper[2], which is the induced charge on the inner surfaces of the metal tubes. If this induced charge is taken into account, we will find that the phase of the moving charge will not change with the electric potential difference between two metal tubes. So, it is more convincing to state that the real factor affecting the phase of a moving charge is the energy of the system including the moving charge and the induced charge, but not the scalar potential itself. The similar conclusions about the magnetic A-B effect[6,10–12] and its theoretical proof[10] have also been proposed before.

The electric A-B effect with induced charges neglected

First, let us repeat the possible experiment proposed by Aharonov and Bohm to demonstrate the electric A-B effect. As depictured in Fig. 1, a coherent charge beam is split into two parts and each part enters

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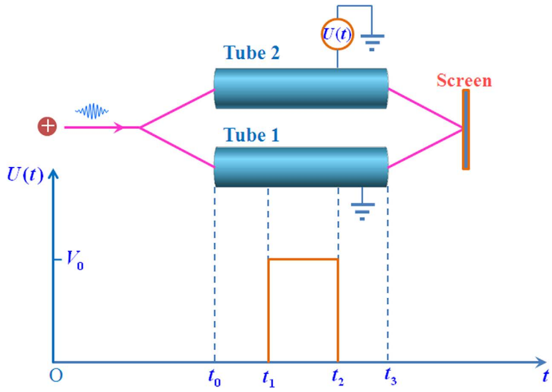

Figure 1. Schematic experiment to demonstrate the electric A-B effect. $U(t)$ represents the external voltage generator. The charge enters into the tubes at $t = t_0$, the external voltage generator is switched on at $t = t_1$, the external voltage generator is switched off at $t = t_2$, then, the charge leave the tubes at $t = t_3$.

into a separate long cylindrical metal tube. After the beams pass through the metal tubes, they are combined to interfere coherently at the screen. By means of time-determining electrical "shutters" the charge beam is divided into wave packets, the length of each wave packet is long compared with its wavelength but short compared with the length of the metal tube. To analysis this experiment in more detail, we suppose the moving charge enter into the metal tubes at t_0, comes out from the tubes at t_3, in addition, $t_0 < t_1 < t_2 < t_3$. During the time interval from t_1 to t_2, while the moving electron is well inside the tubes, an electric potential difference V_0 is applied between these two tubes. For example, the tube 1 is always connected to the zero potential point, and the tube 2 is connected to an external voltage generator, which makes the electric potential of the tube 2 to alternate in time as following:

$$U(t) = \begin{cases} 0 & t < t_1 \\ V_0 & t_1 \le t \le t_2 \\ 0 & t > t_2 \end{cases} \tag{1}$$

To keep the potentials of the two tubes being zero in $t < t_1$ and $t > t_2$, the metal tube 2 should also be connected with the zero potential point in these two time intervals. Otherwise, the collision of the ions and the charges accumulation will make the potential of the tube 2 uncontrollable.

Let's discuss this problem in the following situations:

The first situation. The external voltage generator is switched off, $\psi_1^0(x, t)$ and $\psi_2^0(x, t)$ represent the wave functions of the parts passing through the tubes 1 and 2, respectively, which are unperturbed by the external electric potential; $x\,(x = x_1, x_2, x_3)$ is the coordinate of the moving charge. The total wave function $\psi^0(x, t)$ is:

$$\psi^0(x, t) = \psi_1^0(x, t) + \psi_2^0(x, t) \tag{2}$$

$\psi_1^0(x, t)$ and $\psi_2^0(x, t)$ are determined by the following equations:

$$\begin{cases} i\hbar\frac{\partial}{\partial t}\psi_1^0(x, t) = -\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2}\psi_1^0(x, t) \\ i\hbar\frac{\partial}{\partial t}\psi_2^0(x, t) = -\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2}\psi_2^0(x, t) \end{cases} \tag{3}$$

where $\frac{\partial^2}{\partial x^2} \equiv \frac{\partial^2}{\partial x_1^2} + \frac{\partial^2}{\partial x_2^2} + \frac{\partial^2}{\partial x_3^2}$.

The second situation. The external voltage generator is switched on. $\psi_1(x, t)$ and $\psi_2(x, t)$ represent the wave functions perturbed by the external electric potential. The total wave function $\psi(x, t)$ is:

$$\psi(x, t) = \psi_1(x, t) + \psi_2(x, t) \tag{4}$$

$\psi_1(x, t)$ and $\psi_2(x, t)$ are determined by the following equations:

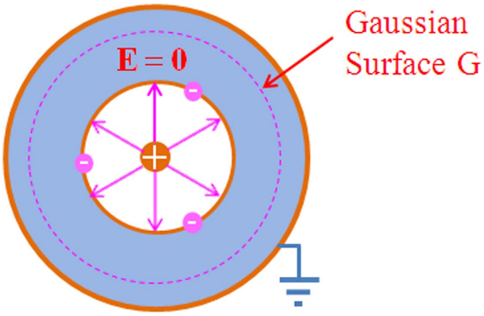

Figure 2. A charge is placed in a metal cavity, the induced charges will appear on the inner surface of metal cavity ensuring that the electric field E at every point within the metal is zero.

$$\begin{cases} i\hbar\frac{\partial}{\partial t}\psi_1(x,\,t) = -\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2}\psi_1(x,\,t) \\ i\hbar\frac{\partial}{\partial t}\psi_2(x,\,t) = -\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2}\psi_2(x,\,t) + qU(t)\psi_2(x,\,t) \end{cases} \tag{5}$$

Then, comparing the eq. (3) and (5), the wave functions $\psi_1(x,\,t)$ and $\psi_2(x,\,t)$ for the charge in the two beams are given by:

$$\begin{cases} \psi_1(x,\,t) = \psi_1^0(x,\,t) \\ \psi_2(x,\,t) = \psi_2^0(x,\,t)\exp\left(\frac{-iq}{\hbar}\int_0^t U(t')dt'\right) \end{cases} \tag{6}$$

When $t > t_2$, the total wave function become:

$$\psi(x,\,t) = \psi_1^0(x,\,t) + \psi_2^0(x,\,t)\exp\left[\frac{-iqV_0(t_2 - t_1)}{\hbar}\right] \quad (t > t_2) \tag{7}$$

Comparing the equations (2) and (7), after the two beams come out from the tubes, an additional phase difference between these two beams appears in the second situation, which is

$$\Delta\varphi = \varphi_1 - \varphi_2 = \frac{qV_0(t_2 - t_1)}{\hbar} \tag{8}$$

So, when these two beams meet at the screen, the interference pattern will change with the value of $qV_0(t_2 - t_1)$.

The discussion above is quite similar to the original paper by Aharonov and Bohm[2], which also appears in some modern quantum mechanics textbooks[19]. But, in the discussion above, no induced charge was taken into account. No induced charge appearing on the surfaces of the metal tubes means that the electric field of the moving charge exists in all the space. So, in these two situations above, the electric field of the moving charge is not zero in the interior of the metal, furthermore, this electric field can penetrate the metal tube and exists in the region outside the metal tubes. Obviously, the discussion above is not reliable in principle. The induced charges should be taken into account.

In classical electrodynamics, if a charge is placed outside a metal surface, the induced charges will appear on the metal surface, where the metal surface is idealized as a mathematical surface of zero thickness. In quantum mechanics, Ref. 20 showed that the induced charges appear in a 0.2 nm thick layer near the metal surface in reality, but, the potential energy between the external charge and the induced charges can be described to a good approximation by the results of classical electrodynamics.

As depicted in the Fig. 2 a charge q is placed in a cavity that is totally within the metal, and the outer surface of the metal is connected to the zero potential point. Suppose the total induced charges on the inner surface is q'. As long as there are free electrons in the metal, the electric field **E** at every point within the metal should be zero. As long as the Coulomb's law holds, or in other words, the potential of a point charge q is $\frac{q}{4\pi\varepsilon_0 r}$, the Gauss's law should hold too. So, if we draw a Gaussian surface G surrounding the cavity, for $\mathbf{E} = 0$ everywhere on the Gaussian surface:

$$\iint_G \mathbf{E}\cdot d\mathbf{S} = \frac{q+q'}{\varepsilon_0} = 0 \tag{9}$$

Then, we have

$$q = -q' \tag{10}$$

The electric A-B effect with influence of the induced charges

So, in experiments, once the moving charge q (suppose $q = \pm e$) get into the metal tubes, an induced charge $q'(q' = -q)$ will appear on the inner surfaces of the metal tubes. (If the moving charge q is a proton, the induced charge q' will be an electron; If the moving charge q is an electron, then the induced charge q' will be a hole in the Fermi gas of the metal tube. The induced charge q' is located on the inner surfaces of the tubes.) At the same time, another induced charge $q''(q'' = q)$ will appear on the outer surfaces of the metal tubes. During the time interval from t_0 to t_1, both the tubes are connected to the zero potential point, so, the induced charge q'' on the outer surfaces of the metal tubes will flow into the zero potential point. Therefore, only the induced charge q' on the inner surfaces of the tubes needs to be taken into account.

When the charge q moves in the metal tubes, for the induced charge q' appears on the inner surfaces of the tubes, the electric field of the moving charge q will be shielded by the induced charge q', and the resultant electric field produced by the charges q and q' only exists in the region enclosed by the inner surface of the metal tubes. For the moving charge q and the induced charge q' attract each other, the coordinate $y(y = y_1, y_2, y_3)$ of the induced charge q' is dependent on the coordinate $x(x = x_1, x_2, x_3)$ of the moving charge q. Therefore, the wave function of the induced charge q' changes with the position of the moving charge q, at the same time, the wave function of the moving charge q is also perturbed by the induced charge q'[21,22]. So, both the moving charge q and the induced charge q' are not free particles, we should take the moving charge q and the induced charge q' as a system. Let $\psi^0(x, y, t)$ and $\psi(x, y, t)$ represent the wave functions of this system with the external voltage generator being switched off or on, respectively.

In the region outside the metal tube (*i.e.* $t < t_0$ or $t > t_3$), the moving charge is a free particle and has no relationship with the induced charges and the potential difference $U(t)$ between the two tubes. So, we need only to discuss the revolution of the wave function of the charges q and q' in the region enclosed by the metal tubes, *i.e.* the time dependence of the wave function from t_0 to t_3.

So, ***the third situation***: the external voltage generator is switched off, but, the induced charge q' is included. Then the total wave function is:

$$\psi^0(x, y, t) = \psi_1^0(x, y, t) + \psi_2^0(x, y, t) \qquad t_0 < t < t_3 \tag{11}$$

where $\psi_1^0(x, y, t)$ and $\psi_2^0(x, y, t)$ represent the wave functions of the parts passing through the tubes 1 and 2, respectively, which are unperturbed by the external electric potential $U(t)$. The wave functions $\psi_1^0(x, y, t)$ and $\psi_2^0(x, y, t)$ satisfy the following Schrödinger equation:

$$\begin{cases} i\hbar\frac{\partial}{\partial t}\psi_1^0(x, y, t) = -\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2}\psi_1^0(x, y, t) + \left\{-\frac{\hbar^2}{2m'}\frac{\partial^2}{\partial y^2}\psi_1^0(x, y, t) + q'\phi(y)\psi_1^0(x, y, t)\right\} + \frac{qq'}{4\pi\varepsilon_0|x-y|}\psi_1^0(x, y, t) \\ i\hbar\frac{\partial}{\partial t}\psi_2^0(x, y, t) = -\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2}\psi_2^0(x, y, t) + \left\{-\frac{\hbar^2}{2m'}\frac{\partial^2}{\partial y^2}\psi_2^0(x, y, t) + q'\phi(y)\psi_2^0(x, y, t)\right\} + \frac{qq'}{4\pi\varepsilon_0|x-y|}\psi_2^0(x, y, t) \end{cases} \tag{12}$$

where, $t_0 < t < t_3$; m' is the mass of the induced charge q'; $\phi(y)$ is the potential function experienced by the induced charge q' in the metal tubes, which ensures that the induced charge q' can only move in the interior of the metal and cannot leave out from the surfaces of the metal tubes, (noticing: $\phi(y)$ is independent of the potential difference $U(t)$ between the two metal tubes.); $|x-y| \equiv \sqrt{(x_1-y_1)^2 + (x_2-y_2)^2 + (x_3-y_3)^2}$; and $\frac{qq'}{4\pi\varepsilon_0|x-y|}$ is the interaction energy between the moving charge q and the induced charge q'.

The fourth situation: the external voltage generator is switched on, and the perturbed wave function $\psi(x, y, t)$ of the system will become

$$\psi(x, y, t) = \psi_1(x, y, t) + \psi_2(x, y, t) \qquad t_0 < t < t_3 \tag{13}$$

where $\psi_1(x, y, t)$ and $\psi_2(x, y, t)$ represent the wave functions perturbed by the external electric potential $U(t)$. $\psi_1(x, y, t)$ and $\psi_2(x, y, t)$ satisfy the following Schrödinger equations:

$$\begin{cases} i\hbar\frac{\partial}{\partial t}\psi_1(x, y, t) = -\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2}\psi_1(x, y, t) + \left\{-\frac{\hbar^2}{2m'}\frac{\partial^2}{\partial y^2}\psi_1(x, y, t) \right. \\ \qquad \left. + q'\phi(y)\psi_1(x, y, t)\right\} + \frac{qq'}{4\pi\varepsilon_0|x-y|}\psi_1(x, y, t) \\ i\hbar\frac{\partial}{\partial t}\psi_2(x, y, t) = -\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2}\psi_2(x, y, t) + \left\{-\frac{\hbar^2}{2m'}\frac{\partial^2}{\partial y^2}\psi_2(x, y, t) \right. \\ \qquad \left. + q'\phi(y)\psi_2(x, y, t)\right\} + \frac{qq'}{4\pi\varepsilon_0|x-y|}\psi_2(x, y, t) \\ \qquad + qU(t)\psi_2(x, y, t) + q'U(t)\psi_2(x, y, t) \end{cases} \tag{14}$$

In the equations (14), $qU(t)$ and $q'U(t)$ are the potential energies of the moving charge q and the induced charge q' in the electric field $U(t)$, respectively. For $q = -q'$, the sum of $qU(t)\psi_2(x, y, t)$ and $q'U(t)\psi_2(x, y, t)$ is zero *i.e.* the interaction energy between q and $U(t)$ is completely counteracted by the interaction energy between q' and $U(t)$. Therefore, the equations (14) will become:

$$\begin{cases} i\hbar\frac{\partial}{\partial t}\psi_1(x, y, t) = -\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2}\psi_1(x, y, t) + \left\{-\frac{\hbar^2}{2m'}\frac{\partial^2}{\partial y^2}\psi_1(x, y, t) \right. \\ \qquad \left. + q'\phi(y)\psi_1(x, y, t)\right\} + \frac{qq'}{4\pi\varepsilon_0|x-y|}\psi_1(x, y, t) \\ i\hbar\frac{\partial}{\partial t}\psi_2(x, y, t) = -\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2}\psi_2(x, y, t) + \left\{-\frac{\hbar^2}{2m'}\frac{\partial^2}{\partial y^2}\psi_2(x, y, t) \right. \\ \qquad \left. + q'\phi(y)\psi_2(x, y, t)\right\} + \frac{qq'}{4\pi\varepsilon_0|x-y|}\psi_2(x, y, t) \end{cases} \tag{15}$$

Now, the potential difference $U(t)$ has disappeared from the eq. (15), *i.e.* the Schrödinger equations (15) are independent of the potential difference $U(t)$, so, the wave functions $\psi_1(x, y, t)$ and $\psi_2(x, y, t)$ should also be independent of $U(t)$. Comparing the equations (12) and (15), which are exactly same to each other, so, the following equations are obvious:

$$\begin{cases} \psi_1(x, y, t) = \psi_1^0(x, y, t) \\ \psi_2(x, y, t) = \psi_2^0(x, y, t) \end{cases} \qquad t_0 < t < t_3 \tag{16}$$

In this situation, the total wave function is:

$$\begin{aligned} \psi(x, y, t) &= \psi_1(x, y, t) + \psi_2(x, y, t) \\ &= \psi_1^0(x, y, t) + \psi_2^0(x, y, t) = \psi^0(x, y, t) \end{aligned} \qquad t_0 < t < t_3 \tag{17}$$

For $\psi(x, y, t)$ is the wave function of the charges q and q' with the external potential difference being $U(t)$, but, $\psi^0(x, y, t)$ is the wave function with the external potential difference being zero, $\psi(x, y, t) = \psi^0(x, y, t)$ means that the wave function will not change with the potential difference $U(t)$. So, when the two beams meet at the screen, the interference pattern will not change with $U(t)$, *i.e.* the phase shift as eq. (8) predicted by the electric A-B effect will not appear.

Discussions and Conclusions

Why does not the phase shift predicted by the electric A-B effect appear if the induced charge is included? Because, if there were no induced charge on the surfaces of the metal tubes, the electric field of the moving charge would exist in all the space, this field could penetrate the metal tubes and overlap with the electric field between the two tubes applied by the external voltage generator. While the moving charge q is in the tube 2, its potential energy is $qU(t)$; while the moving charge q is in the tube 1, its potential energy is 0. According to quantum mechanics, the wave function of the moving charge is:

$$\psi(x, t) = \psi_1(x, t) + \psi_2(x, t) = \varphi_1(x)e^{-iE_1t/\hbar} + \varphi_2(x)e^{-iE_2t/\hbar} \tag{18}$$

where E_1 and E_2 are the energies of the parts passing through the tube 1 and 2, respectively. They are given by:

$$\begin{cases} E_1 = E_K \\ E_2 = E_K + qU(t) \end{cases} \tag{19}$$

where E_K is the kinetic energy of the moving charge. Obviously $E_1 \neq E_2$, so, the time dependence of the $\psi_1(x, t)$ is different with that of $\psi_2(x, t)$. Therefore, when these two beams come out from the tubes, a phase shift due to the potential difference $U(t)$ between the tubes will appear, this is the electric A-B effect predicted by Aharonov and Bohm. This analysis is consistent with the eq. (8). The eq. (8) shows the phase shift $\Delta\varphi$ is proportion to qV_0, which represents the potential energy of the moving charge q. So, the eq. (8) strongly implies the phase shift $\Delta\varphi$ arise from the interaction energy between the moving charge q and the electric field $U(t)$[6].

But in a real experiment, when the moving charge q moves in the metal tubes, there must be an induced charge q' appearing on the inner surfaces of the metal tubes. Just for the appearance of the induced charge q', the resultant electric field produced by the moving charge q and the induced charge q' can only exist in the region enclosed by the inner surfaces of the metal tubes. So, this resultant electric field cannot overlap with the electric field between the tubes. The potential energy (related to $U(t)$) of the system including the moving charge q and the induced charge q' is zero no matter the moving charge q is in the tube 1 or tube 2. The wave function of the system:

$$\psi(x, y, t) = \psi_1(x, y, t) + \psi_2(x, y, t) = \varphi_1(x, y)e^{-iE_1t/\hbar} + \varphi_2(x, y)e^{-iE_2t/\hbar} \tag{20}$$

where, E_1 is the energy of the system with the moving charge passing through the tube 1, E_2 is the energy of the system with the moving charge passing through the tube 2. E_1 and E_2 are given by:

$$\begin{cases} E_1 = E_K + E_K' + q'\phi(y) + \dfrac{qq'}{4\pi\varepsilon_0|x - y|} \\ E_2 = E_K + E_K' + q'\phi(y) + \dfrac{qq'}{4\pi\varepsilon_0|x - y|} + qU(t) + q'U(t) \end{cases} \tag{21}$$

where, E_K and E_K' are the kinetic energies of the moving charge q and the induced charge q'; the other quantities are defined as above.

For $q = -q'$, so:

$$\begin{cases} E_1 = E_K + E_K' + q'\phi(y) + \dfrac{qq'}{4\pi\varepsilon_0|x - y|} \\ E_2 = E_K + E_K' + q'\phi(y) + \dfrac{qq'}{4\pi\varepsilon_0|x - y|} \end{cases} \tag{22}$$

Obviously,

$$E_1 = E_2 \tag{23}$$

So, the time dependence of $\psi_1(x, y, t)$ is same to that of $\psi_2(x, y, t)$. Therefore, when these two beams come out from the tubes, no phase shift due to the potential difference $U(t)$ will appear. When these two parts meet at the screen, the interference pattern will not change with the potential difference $U(t)$ between the two tubes.

In this situation, the potential difference $U(t)$ between the two metal tubes still exists, but the phase shift due to $U(t)$ does not appear. So, it is difficult to state the scalar potential can affect the phase of a moving charge; it is more reasonable to state that the real factor affecting the phase of a moving charge should be the potential energy of the system including the moving charge q and the induced charge q'.

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