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Experimental observation of time-delays associated with electric Matteucci–Pozzi phase shifts

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Abstract. In 1985, Matteucci and Pozzi (1985 *Phys. Rev. Lett.* **54** 2469) demonstrated the presence of a quantum mechanical phase shift for electrons passing a pair of oppositely charged biprism wires. For this experimental arrangement no forces deflect the electrons. Consequently, the result was reported as a non-local type-2 Aharonov–Bohm effect. Boyer (2002 *Found. Phys.* **32** 41–50; 1987 *Nuovo Cimento B* **100** 685–701) showed theoretically that the Matteucci–Pozzi effect could be associated with a time delay caused by a classical force. We present experimental data that confirm the presence of a time delay. This result is in contrast to the situation for the original magnetic Aharonov–Bohm effect. On similar theoretical grounds, Boyer has also associated classical forces and time delays with the magnetic Aharonov–Bohm effect. Recently, we reported the absence of such observable time delays. The contrast with our current work illustrates the subtle nature of Aharonov–Bohm effects.

In their now famous 1959 paper [1], Aharonov and Bohm (AB) outlined two experiments to demonstrate effects that are purely quantum mechanical in nature. While this view has generated much discussion and controversy, it is now generally accepted that the effects AB outline illustrate the manner in which electromagnetic potentials can influence a system without a classical force present. AB proposed the use of magnetic flux enclosed in an electron interferometer to cause the phase shift [1]. Chambers, following the proposal, demonstrated the now famous magnetic (or vector) AB-effect [2]. Later efforts [3–6] include Tonomura’s

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beautiful experiments using magnetic toroids. Excellent agreement was found between the measured phase shift and the theoretical prediction:

$$\Delta\varphi_{AB} = -\frac{e}{\hbar} \oint_c \vec{A}(\vec{l}) \cdot d\vec{l} = -\frac{e}{\hbar} \phi_B, \quad (1)$$

where the magnitude of the charge of the electron is e , the vector potential is \vec{A} and the contour encloses the magnetic flux ϕ_B of a solenoid.

In 2002, Boyer proposed that an electron passing by a magnetic line of flux would experience a force that would give rise to a time delay [7]. This time delay in a semi-classical theory gives rise to a phase shift $\Delta\varphi = \frac{1}{\hbar} p_y \Delta y$ that exactly matches the AB-phase shift $\Delta\varphi_{AB}$. However, a fully classical experiment detected no force; no time delays were observed after passing electron pulses by a solenoid [8].

The other experiment that AB described is usually referred to as the electric (or scalar) AB-effect. In this case, the electron interferometer arms enclose the electric field \vec{E} between the capacitor plates. Fringing fields are reduced by replacing the capacitor plates with cylindrical metal tubes that can be kept at different electric potentials. To eliminate the effect of fringe fields, the proposed electron source is either pulsed or chopped, and the electric potential raised and lowered only when the electron wave packets are well inside the tubes. The phase difference is given by

$$\Delta\varphi_{SAB} = -\frac{e}{\hbar} \oint V(t) \cdot dt = -\frac{e}{\hbar v} \left| \int \vec{E} \times d\vec{S} \right|, \quad (2)$$

where $V(t)$ is the time-dependent potential applied to the cylindrical tubes. However, unlike the magnetic AB-effect, the electric AB-effect has never been experimentally realized in the pulsed version that AB originally described.

In 1985 Matteucci and Pozzi (MP) published [9] a steady-state version of the electric AB-effect. This was considered ‘a simple and convincing demonstration of the type-2 non-local phenomenon predicted by Aharonov . . .’ The difference between a type-1 and type-2 non-local effect is that in the first case (such as the Aharonov–Bohm effects) the electron never passes through a field, while in the Matteucci–Pozzi case the electron passes straight through the field. In MP’s beautiful experiment, the contact potential between two adjacent metal layers in a wire produces a field that is the equivalent of two oppositely charged, parallel biprism wires in close proximity. The special feature of a single biprism wire is that deflection of passing electrons is independent of distance from the wire (in the impulse approximation). This means that the deflection from two oppositely charged wires is zero. Nevertheless, the phase accumulated by the electron on one side of the wires is different than the phase accumulated on the opposite side, and the result is a phase without a force phenomenon (figure 1 top) [10].

The claim that the MP-experiment was a demonstration of a type-2 effect was challenged by Boyer in 1987 [11]. Boyer argued that the phase shift had a clear explanation due to an electrostatic lag effect associated with a longitudinal force (figure 1 bottom). In the MP-work only transverse forces causing deflection were considered. In this paper we give an experimental confirmation of a classical time delay for electrons passing near a pair of oppositely charged wires, as predicted by Boyer [11].

To determine the presence of a delay, we performed a conceptually very simple, classically motivated experiment. The flight time of an electron passing by two parallel, oppositely charged wires is determined (figure 2). The wire pair consists of two 35-gauge (143 μm diameter) bare copper wires. The wires are mounted in the vacuum chamber separated by about 1 mm.

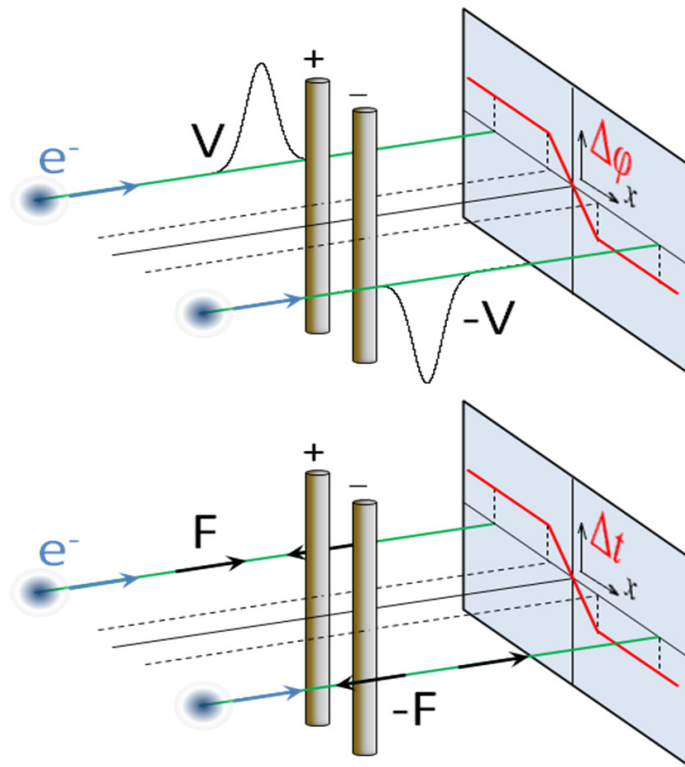


Figure 1. Phase versus delay. Top: Aharonov suggested, and Matteucci and Pozzi predicted and demonstrated, a phase shift for electrons passing by oppositely charged wires. This phase shift was attributed to a forceless, type-2 AB-phase effect [9]. Bottom: Boyer [7, 11] predicted that electrons passing this wire pair would experience a time delay caused by a classical force. For a detailed explanation see text.

One wire is held at a positive voltage, while the other is held at an equal-magnitude negative voltage. Electrons are emitted via laser induction from a field emission tip [12] that is held at $V_{\text{tip}} = -70$ V. Electrons travel from the tip through a grounded pinhole into a region with a scalar potential associated with the two charged wires. The center of the pinhole is positioned about 4 mm from the nearest wire. Magnetic shielding (μ -metal) is used in this region to reduce external magnetic fields. After passing the wires, the electrons hit a multi-channel plate (MCP) electron detector. The travel time of the electrons from the tip to the detector is measured. The laser system's trigger signal provides a start time, while the MCP's electron detection signal provides a stop time. A time-to-amplitude converter (TAC) is used to process the signals to generate time spectra. The laser (Spectra Physics Tsunami oscillator) used to induce electron emission has a 75 MHz repetition rate, which provides a 13-nanosecond window for the temporal spectra. This timing mechanism has been used with a drift tube to produce an energy analyzer [12], measure the electron width of the electron pulses emitted from this source [13] and determine the lack of classical forces for electrons passing a solenoid [8].

Temporal spectra are taken with different voltages on the wires. Example spectra are shown in the inset of figure 3 (top right). Each temporal spectrum is fitted with a Gaussian curve. The center of this Gaussian curve fit is taken to be the arrival time of the electron pulse for

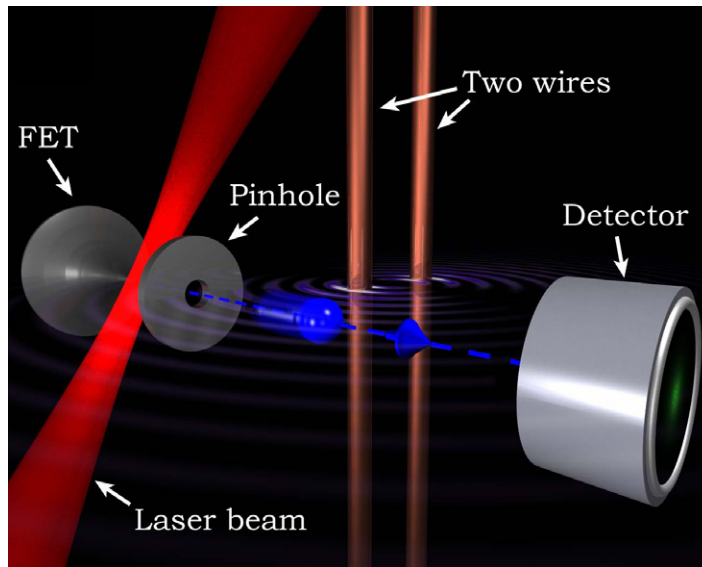


Figure 2. Experimental system. Electrons are emitted via laser induction from a field emission tip (FET), travel through a scalar potential associated with two oppositely charged wires and have their arrival times at the detector measured. A grounded plate with a pinhole shields the emitted electrons from the scalar field region until passing through the pinhole.

that wire voltage configuration (shown as solid circles in figure 3, the colored data points correspond to the time spectra in the inset). The absolute zero of these spectra is not well-defined because the travel time of the electrons is larger than the time between consecutive laser pulses. Consequently, only relative time delays are measured. The zero on the time delay data is chosen to be the arrival time with no wire voltage (the insets have not been shifted in time).

The results on the arrival time by the experiment (and the simulation explained below) are compared to predictions made by Boyer [7, 11].

To estimate the arrival time as predicted by Boyer, the y -coordinate of the force, parallel to the electron velocity, is needed. This component of the force exerted by the electron on the line charges is given by Boyer [7, 11] to be

$$F_{\text{dip}}^y = -e\wp \frac{4xy}{4\pi\epsilon_0(x^2 + y^2)^2}, \quad (3)$$

where x and y are the xy -coordinates of the electron, and \wp is the dipole moment per unit length. As non-relativistic, electrostatic forces satisfy Newton's third law, the force of the line charges on the particle is equal and opposite, $\vec{F}_e = -\vec{F}_{\text{dip}}$.

To be able to compare equation (3) with our experimental system some steps need to be taken. First, the limits of integration are changed to match the physical limits of our experiment. The spatial displacement, Δy , is obtained by integrating the force twice over time. The temporal delay, Δt (figure 3 dashed line), is approximated by $\Delta t = \Delta y/v_0$, where v_0 is the initial velocity of the electrons. As an aside, it is noted that the phase shift is obtained by making the semi-classical argument that $\Delta\varphi = k\Delta y$, where k is the wavevector associated with the particle, based

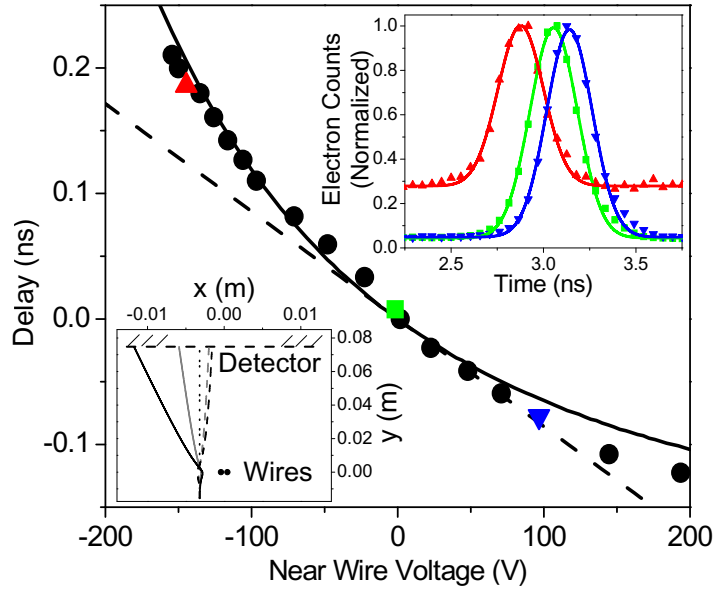


Figure 3. Arrival time measurements. Arrival times (circles) for electron pulses passing two wires charged at equal magnitude and opposite sign voltages are determined from temporal spectra by a time-of-flight method. Example spectra corresponding to the triangular and square data points are shown in the top inset. The data is compared to a simulation (solid curve) that calculates the trajectories of the electrons passing the wire pair. The experimental results are also compared to the delay predicted by Boyer [7, 11] (dashed curve). In the lower inset, sample electron trajectories are shown for 70 eV electrons. Starting from the left, trajectories are shown with nearest wire voltage set at +200 V (solid black curve), +100 V (solid gray curve), 0 V (dotted black curve), -100 V (dashed gray curve) and -200 V (dashed black curve).

on the analytical identity (for this physical system)

$$\frac{1}{\hbar} \int_{-\infty}^{\infty} V dt = k \int_{-\infty}^{\infty} \int_{-\infty}^t \frac{1}{m} F_y dt' dt, \quad (4)$$

where the left-hand side is motivated by quantum mechanics and the right-hand side by the semi-classical argument. For our current reasoning the temporal delay $\Delta t = \frac{1}{v_0} \int_{-\infty}^{\infty} \int_{-\infty}^t \frac{1}{m} F_y dt' dt$ is needed. Thus, the second step is to obtain the needed force from the potential. This step is motivated by the fact that the experimental configuration determines the parameters that set the potential. Two oppositely charged wires are described as infinitely long cylinders with radius R held at fixed voltages. The wires are positioned at $x = \pm x_0$ and $y = 0$, with the wire positioned at $x = +x_0$ set to a voltage of $V = +V_0$ and the wire at $x = -x_0$ held at $V = -V_0$. The potential in the plane perpendicular to these wires is

$$V(x, y) = \frac{V_0}{2 \operatorname{arccosh}(x_0/R)} \ln \left(\frac{x^2 + y^2 + d^2 + 2xd}{x^2 + y^2 + d^2 - 2xd} \right), \quad (5)$$

where the constant $d \equiv \sqrt{x_0^2 - R^2}$ has been defined [14]. Electron pulses propagate in the y -direction and pass beside the wire pair (i.e. $|x| > x_0$). The components of the force acting

on the electrons due to the scalar potential field produced by the wire pair is given by

$$F_x = -q \frac{\partial V(x, y)}{\partial x} = \frac{eV_0}{\operatorname{arccosh}(x_0/R)} \left[\frac{x+d}{x^2+y^2+d^2+2xd} - \frac{x-d}{x^2+y^2+d^2-2xd} \right], \quad (6)$$

$$F_y = -q \frac{\partial V(x, y)}{\partial y} = \frac{eV_0}{\operatorname{arccosh}(x_0/R)} \left[\frac{y}{x^2+y^2+d^2+2xd} - \frac{y}{x^2+y^2+d^2-2xd} \right], \quad (7)$$

where the electron charge $q = -e$ has been used. Assuming that the wires are much closer together than the distance between the electron path and the wires (i.e. $x \gg d$), equation (7) can be reduced to

$$F_y = \frac{eV_0}{\operatorname{arccosh}(x_0/R)} \left[\frac{-4xyd}{(x^2+y^2+d^2+2xd)(x^2+y^2+d^2-2xd)} \right] \approx -\frac{e\wp}{4\pi\epsilon_0} \frac{4xy}{(x^2+y^2)^2}, \quad (8)$$

where the voltage on the wire, V_0 , is related to the dipole moment per unit length, \wp , by Boyer [11]

$$V_0 = \frac{\wp \operatorname{arccosh}(x_0/R)}{4\pi\epsilon_0 d}. \quad (9)$$

The resulting expression for the y -component of the force on the electron pulse by the wire pair in equation (8) matches the expression for the force found by Boyer [7, 11]. This means we can obtain two time delays. The first time delay is based on Boyer's force expression, which is a crude approximation, and a second time delay can be obtained by simulating the trajectories by integrating Newton's equation using equations (6) and (7) directly, which gives an improved approximation.

In the simulation, the effect of transverse deflections and changing velocities is taken into account. In this way, the validity of the two approximations used to arrive at Boyer's expression in the previous paragraph are tested. The electrons are assumed to begin with a velocity pointed in the $+y$ -direction (the transverse position). In figure 3 (bottom left), some example trajectories are shown for 70 eV electrons. The electrons are assumed to initially travel perpendicular to the wires starting at the experimentally specified distance from the nearest wire (4 mm in the negative x -direction). The electrons are started in the simulation at the experimental location of the pinhole (~ 15 mm in the negative y -direction). The energy of 70 eV is chosen, because at that energy the electrons would start to show effects of transverse deflection. The deflection asymmetry in the trajectories with respect to the sign of the voltage is due to an increased deflection when the closer wire has a positive as opposed to a negative voltage. The end result of the simulation is the calculated delay in arrival time, which is indicated by the solid line in figure 3.

In figure 3 the main result of this letter is shown: *the slopes of the experimental data, the theory and the simulation are in agreement around zero applied wire voltage*. This should be compared to the prediction for the case where the MP experiment was a type-2 AB-effect; all measured delays and the slope would have been zero. It is clear that the experiment favors a non-zero slope around zero voltage that is close to Boyer's prediction. This also justifies (in this region) the assumption that sideway deflections are negligible, in agreement with the ideas of Matteucci *et al* [9]. To further motivate the conclusion that sideway deflections are negligible, notice that figure 3 shows at 200 V that the assumption of a straight trajectory is not correct, but is good at tens of volts. Secondly, the particle passes by a dual biprism. One wire is at positive

and the other at equal magnitude negative voltage. Thus, one wire lowers the potential of the other. Thirdly, the particle stays at some distance from the dual biprism wires, further lowering the potential that the particle experiences. This ensures that the kinetic energy is always much larger than the potential energy. The simulation illustrates this further. The deflection even at a 100 V dual biprism setting is less than 1 cm in the x -direction for about 8 cm traveled in the y -direction (notice that the vertical and horizontal scales are not the same). This justifies the straight path and impulse approximation.

For larger wire voltages, the experimental data and the simulation deviate slightly. Also, the experimental data does show some scatter, which cannot be attributed to statistical fitting error. The fitting error is limited to about 0.05 ns, as illustrated in the upper right inset of figure 3. This scatter and deviation can be attributed to experimental details such as irregularities in wire shape and straightness, details of the shape of the wire holder, and also assumptions in the simulation. The simulation assumes no spread in velocity or position of the electrons coming into the region affected by the wires. The electrons are also assumed to have a velocity vector perpendicular to the wires. Experimentally, the pinhole limits spatial spreading, but there is some temporal spread and energy width.

Overall, a time delay is observed that agrees with Boyer's prediction. This shows that the MP-experiment does not demonstrate a true type-2 AB-effect. It is interesting to compare this to the magnetic AB-effect. The same experimental and theoretical approaches applied to an electron passing by a solenoid results in a phase shift that is identical to that predicted by Aharonov and Bohm. However, it was shown experimentally that no classical time delays are present for electrons passing a solenoid [8]. Furthermore, the magnetic AB-phase shift occurs in experimental configurations where fields are shielded or no evidence of classical forces is shown; thus, it is generally considered purely quantum mechanical in nature. The MP-phase shift (which is the electric AB-phase shift for a steady-state system) is very different. The MP phase shift occurs in the presence of classical forces, and it is exactly these forces that shift the wave packet by an amount that explains the MP-phase shift.

It may be disconcerting that phase shift, a quantum mechanical concept, and force, a classical concept, are mixed in the above discussion. The argumentation, though, can be placed on more solid ground. A classical deflection occurs when a particle beam experiences a potential gradient (i.e. a force) orthogonal to its direction of motion. The correspondence principle demands that quantum mechanics must also predict a deflection. Consider multiple parallel paths such as are relevant in the path integral description of a particle beam. The potential gradient ensures that these parallel paths accumulate a different phase, which leads to constructive interference in a deflected direction. Experimentally, the center of weight of the beam is displaced in the detection plane that is oriented with its normal along the original direction of motion of the beam. In the forward direction a similar argument can be made. A particle beam which runs over a stationary potential hill experiences a potential gradient along its direction of motion and the particle suffers a classical delay. As compared to the deflection example, a complication is that the potential hill will not have changed the particle velocity after passing over the hill, but will nevertheless arrive later than identical particles that did not pass over the hill. The quantum mechanical correspondence bears itself out when considering the velocity (or momentum) components of a wave packet. Lower velocity components will experience larger phase shifts than higher velocity components and the group velocity of the wave packet changes in such a way that the wavepacket is delayed. Experimentally, the center of weight of the beam is displaced if detected along the original direction of motion of the beam.

As Zeilinger [15] originally pointed out, the situation is quite different in an Aharonov–Bohm case. In such a case, the phase shifts associated with different components of a wavepacket are independent of velocity (and position). This is called the dispersionless nature of the Aharonov–Bohm effect. Sadly, this behavior has never been observed for the magnetic AB-effect, while the electric AB-effect has not been observed at all [10]. A dispersionless effect will lead to a measurable phase shift in an AB experiment such as the famous experiment of Chambers [2], but is claimed not to be accompanied by any modification of group velocity. Experimentally, fringes will be observed outside of the coherence length and no displacement of the center of weight of a wavepacket will be observed.

Given that AB-effects are rare and fundamental in nature, it is important to thoroughly investigate such effects. The MP-effect, under investigation in this paper, was originally claimed to be an AB-effect and as such should be dispersionless (in terms of quantum mechanics) or without force (in terms of classical mechanics), or without displacement (in experimental terms). In the original idea, an interesting property of a single charged biprism wire was exploited. A charged particle passing by such a wire deflects by an amount that is independent of the distance to the wire. This means that for equally and oppositely charge biprism wires no deflection is present, or in other words the phase shift accumulated along a straight path is independent of distance to the wire, but opposite for paths passing left or right of the dual biprism wires. The original experimental data presented by Matteucci and Pozzi [9] demonstrates the presence of a phase shift; however, the data presented in this paper show the presence of a force, albeit one that is directed along the direction of motion, indicating that the phase shift is not an AB-effect.

Boyer's approach of utilizing Newton's third law apparently fails for the magnetic AB-effect, while it holds for the MP-effect. Given the almost identical approach for both results, it is interesting to scrutinize. The failure of the approach could lie in the presence of additional momentum terms in the electron–solenoid system [16, 17]. These 'hidden momentum' terms, as they are often called, dictate a different equation of motion for the force on the solenoid than that used by Boyer [16–18]. Although the concept of hidden momentum is questioned by Boyer [19], it appears to be generally accepted that momentum conservation can be satisfied without requiring a back-action [20, 21]. In other words, it is generally accepted that Newton's third law of motion, i.e., the conservation of mechanical momentum for closed systems, is not generally valid. Instead, for closed systems conservation of mechanical plus electromagnetic momentum holds. However, the authors are unaware of any experiments other than Aharonov–Bohm-type experiments where such a violation is evident. The reported experiment on the MP-effect, taken together with the magnetic AB-effect, serves to illustrate this subtlety of AB-type effects.

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