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Why is the transference theory of causation insufficient? The challenge of the Aharonov-Bohm effect

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A B S T R A C T

The transference theory reduces causation to the transmission (or regular manifestation) of physical conserved quantities, like energy or momenta. Although this theory aims at applying to all fields of physics, we claim that it fails to account for a quantum electrodynamic effect, viz. the Aharonov-Bohm effect. After having argued that the Aharonov-Bohm effect is a genuine counter-example for the transference theory, we offer a new physicalist approach of causation, ontic and modal, in which this effect is embedded.

1. Introduction

The transference theory reduces causation to the transmission (or regular manifestation) of physical conserved quantities, like energy or momenta (Dowe, 2000; Kistler, 2006). It is a major physicalist or ontic approach of causation, an approach that provides an account of causation as a physical process, based on our best scientific theories. As Dieks emphasizes, such an account maintains causation in "its rightful place as a category of physical ontology" (1986, p. 85). This theory of causation presumably applies to all fields of physics, like classical mechanics, relativistic physics as well as quantum physics. In particular, quantum electrodynamics is viewed as exemplifying the transference theory of causation: Interactions between charged particles and electromagnetic fields can be expressed via exchanges of physical quantities via photons. For instance, Salmon (1997), one of the first defenders of this account, argues for this claim:

> According to our best contemporary theory, quantum electrodynamics, the electromagnetic force is mediated by exchanges of photons. This means, in my terms, that whenever a photon is emitted or absorbed by a charged particle we have a causal interaction. Thus a charged particle undergoing acceleration in an electromagnetic field consists of a series of *causal processes* standing between frequent *causal interaction*. (Salmon, 1997, p. 465. Our emphases)

In this paper, we nevertheless claim that the transference theory fails to account for a quantum electrodynamic effect, which is the Aharonov-Bohm (AB) effect. We have to carefully pay attention to this effect. First, it is not a singular effect but is, more generally, a particular case of class of different quantum phenomena (Berry, 1984). More to the point, as we will argue for, the AB effect is a paradigmatic case of causal phenomena. This paper thus aims at showing that the AB effect is a counter-example for the transference theory in its current form but, also, at offering a new physicalist approach of causation in which this effect is embedded.

The AB effect is a quantum effect showing that an electronic interference pattern can be modified via an electromagnetic field that is completely shielded from the electrons themselves. This effect, predicted by Aharonov and Bohm (1959), has been well

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confirmed by experiments (Chambers, 1960; Tonomura et al., 1986), and has found various applications with materials (Bachtold et al., 1999; Zaric et al., 2004; van Oudenaarden, Devoret, Nazarov, & Mooij, 1998). Such a phenomenon raises important questions for the foundations of physics. Healey (1997) has discussed in what sense this phenomenon exhibits *non-locality* and *non-separability*. On the other hand, Liu (1994, 1996) has argued for the reality of wave packets based on the AB effect. In this paper, we are interested in the AB effect with regard to the concept of causation and the transference theory. To our knowledge, there is a single discussion on the AB and its consequences on physical causation (Zangari, 1992). However, it does not explicitly tackle the transference theory. Zangari rather defends that the notion of potential has to be added to account for physical causation. Although we agree with his approach, it is a worthy project to investigate in what sense the AB effect makes the transference theory controversial, and to show how it is possible to reconsider this theory in order to account for this phenomenon. Our project is not thus to reject merely the transference theory based on the analysis of the AB effect. Although we argue that the transference theory is not capable of accounting for a paradigmatic case of causation, we suggest how this theory could be revised for that purpose. We propose a view of physical causation based on the core notions of *propagation* and *interaction*.

The paper is structured as follows. First, we outline the main claims of the transference theory and sketch some possible issues (Section 2). We then turn to the AB effect by arguing that it cannot be a case of the transference theory (Section 3). Although the transference theory fails to account for this phenomenon, we then argue that the AB is nevertheless a paradigmatic case of causation (Section 4). Finally, we suggest how to reconsider the theory of transference, and offer a new physicalist approach of causation that includes the AB effect (Section 5).

2. The transference theory and possible counter-examples

Let us begin by introducing the transference theory and then its usual counter-examples as discussed in the literature.

2.1. The transference theory

According to the transference theory, causation reduces to the transmission (or regular manifestation) of a physical quantity from an event *A* to an event *B*. This theory comes from ideas of Aronson (1971a, 1971b) who suggests that "Prior to the time of the occurrence of *B*, the body that makes contact with the effect object possesses a quantity (e.g., velocity, momentum, kinetic energy, heat, etc.) which is *transferred* to the effect object (when contact is made) and manifested as *B*"(1971b, p. 422). Aronson makes clear that causation corresponds to the transference of a physical quantity. However, such a quantity is not clearly identified: it can be "heat" as well as "velocity", which are very different from a physical point of view since, for instance, heat can be dissipated and velocity is not a conserved quantity in elastic collisions. Fair (1979) offers a similar account of causation but focuses on "energy" and/or "momentum" as transferred quantities. The identification of these quantities comes from physicists' empirical investigations, as empirical facts.[1]

On the other hand, Salmon (1977, 1980, 1984) also provides a physicalist – even though quite different – theory of causation, the *theory of mark transmission*. In this approach, there are two distinct causal ingredients. On the one hand, there are causal processes that transmit marks, i.e., propagate some quantities, sometimes defined as processes that transmit energy (1984, p. 146). On the other hand, there are causal interactions, which correspond to the intersection of two causal processes. Following these different approaches, Dowe (1992a, 1992b, 2000) offers a unified theory, namely the *conserved quantity theory*, which is defined as follows:

The conserved quantity theory can be expressed in just two propositions:

> CQ1. A *causal process* is a world line of an object that possesses a conserved quantity.
> CQ2. A *causal interaction* is an intersection of world lines that involves exchange of a conserved quantity. (2000, p. 90)

A *causal interaction*, like the collision between two billard balls, is thus defined via the exchange of conserved physical quantities, viz. energy and momentum. Similarly, Kistler (1998, 2006) argues for a transference theory based on the notion of transfer (or regular manifestation) of physical conserved quantities between distant events. His theory is defined by the statement (S) as follows:

> (S) Two events *c* and *e* are related as cause and effect if and only if there is at least one conserved quantity *P*, subject to a conservation law and exemplified in *c* and *e*, a determinate amount of which is transferred between *c* and *e*. (2006, p. 26)

By "transference", it is explicitly meant that "an amount *A* is said to be transferred between *c* and *e*, if and only if this very amount is present in both events" (Kistler, 2006, p. 26). Despite several differences between Dowe's and Kistler's approaches, causation is defined in both cases as the *transfer* of a physical conserved quantity. Therefore, the decisive rebuttal for this theory would be to exhibit a paradigmatic case of causal relations between two events that would *not* involve any transference of conserved quantity.

2.2. Possible counter-examples

There have been many critical discussions against the transference theory of causation. Most of them have consisted in raising counter-examples in order to argue that the transference of conserved quantities is neither a necessary nor a sufficient condition for causation. For instance, counter-examples based on causation by *disconnection* (Schaffer, 2000) have been raised. In those cases, although two events *C* and *E* are causally related – at least in a counterfactual sense – there is no exchange of a conserved quantity because of a lack of intrinsic connection between *C* and *E*. This could happen when (i) something prevents the exchange of a quantity – energy for instance – between two events *C*′ and *E*, and (ii) *C* is an event that releases this prevention. As a result, *C* causes *E* although there is no transference of conserved quantities between *C* and *C*′. An paradigmatic example is a weight that accelerates because the stretched spring to which it is attached is unblocked. The usual reply for this kind of objection is to deny that those cases are genuinely causal. In particular, Aronson argues for the distinction between a *cause*, which involves transference of conserved quantity and an *occasion*, which is only "a condition that enables the cause to act"(1971a, p. 425). The release of a prevention is not a cause but what makes possible the cause to act.

Conversely, it has been argued that conserved quantities can be transmitted without characterizing a causal relation. This objection comes with *misconnection* (Dowe, 2000, p. 147; Schaffer, 2001). For instance, there is transmission of a certain quantity of billard chalk between a pool cue and a billard ball. However, this exchange of

[1] It should be noted that the transference theory is just a new take on a old debate about modality, namely how to understand metaphysically the basic concepts of propagation and production (Schrenck, 2016).

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