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Restoring particle phenomenology

Giovanni Valente

Cathedral of Learning, 1001 CL, Pittsburgh, PA 15260, United States

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ABSTRACT

No-go theorems are known in the literature to the effect that, in relativistic quantum field theory, particle localizability in the strict sense violates relativistic causality. In order to account for particle phenomenology without particle ontology, Halvorson and Clifton (2002) proposed an approximate localization scheme. In a recent paper, Arageorgis and Stergiou (2013) proved a no-go result that suggests that, even within such a scheme, there would arise act–outcome correlations over the entire spacetime, thereby violating relativistic causality. Here, we show that this conclusion is untenable. In particular, we argue that one can recover particle phenomenology without having to give up relativistic causality.

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1. Introduction

Quantum field theory is our best candidate for a relativistic version of quantum mechanics. Although it has been confirmed experimentally, the jury is still out as to what the fundamental constituents of matter it purports to describe really are. In principle, its ontology would lend itself to either a particle interpretation or a field interpretation. Yet, underlying much of contemporary experimental physics aiming at testing the theory there seems to be a particle ontology, in that one employs procedures designed for the detection of particles: for instance, scattering experiments presuppose the existence of particle trajectories. In fact, the phenomenology of quantum field theory appears as a particle phenomenology. A necessary condition for particle ontology is that particles possess a position, so that they can actually be localized within some spacetime region where a detector is set up. Nevertheless, various no-go theorems against particle localization in relativistic quantum theory have been proven (Hegerfeldt, 1998; Malament, 1996; Redhead, 1995; Reeh & Schlieder, 1961). Accordingly, a particle ontology would become untenable. If so, though, one still ought to account for the observed experimental phenomena, which appear as particle detections. That is, how can one sustain a particle phenomenology without particle ontology?

Halvorson and Clifton (2002) proved a series of no-go results generalizing the previous theorems against particle localization: under mild relativistic constraints, the concept of localizability can be shown to be in conflict with the requirement of relativistic causality, taken more precisely as the condition of microcausality (also referred to as Einstein's principle of causality). They take this as ruling out a particle interpretation of quantum field theory. Then, in the attempt to "salvage the appearances" observed in the laboratory, they developed a procedure to account for particle phenomenology in Algebraic Quantum Field Theory based on an approximate localization scheme resorting to the notion of almost local observables, which, they say, one can adopt for all practical purposes. In an interesting recent paper, Arageorgis and Stergiou (2013) cast Halvorson and Clifton's scheme within the framework of "minimally statistically faithful particle detection experiments", and they proved a no-go theorem that suggests that appealing to almost local observables is still at variance with relativistic causality, in that measurements of such observables would entail act–outcome correlations over the entire spacetime. Here, we show that this conclusion is ungrounded. In fact, we claim that, although Arageorgis and Stergiou's result is certainly correct and deserves close attention, it does not raise any conflict with relativistic causality, nor any threat of act–outcome correlations. In particular, we wish to argue that one can still recover particle phenomenology without having to give up relativistic causality.

We first recall the notion of microcausality and its connection with the absence of act–outcome correlations in Algebraic

E-mail address: valente@pitt.edu

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Quantum Field Theory, and we spell out the consequences of the Reeh–Schlieder theorem for the problem of particle localizability (Section 2.1). Then, we review Halvorson and Clifton's attempt to salvage particle phenomenology without particle ontology (Section 2.2). In the following section, we present Arageorgis and Stergiou's no-go result together with the interpretation proposed by the authors. In Section 4 we show that their theorem is not in contradiction with relativistic causality taken as microcausality; whereas in Section 5 we explain in what sense it does not entail act–outcome correlations extending over the entire spacetime. Finally, we conclude by using our analysis so as to answer the question Arageorgis and Stergiou raised in the title of their paper, that is "How Much Local is Almost Local?".

2. Particle phenomenology without particle ontology

2.1. Localizability and relativistic causality

Halvorson and Clifton (2002) no-go theorems support arguments against the possibility of localizing a single particle, where localizability is formalized in terms of a position operator associated with some bounded region of space, no matter how large. Algebraic Quantum Field Theory offers the prospect to capture spacetime localizability in a different way. In fact, in this framework relativistic quantum field systems are described by mapping $\mathcal{O} \longmapsto \mathcal{R}(\mathcal{O})$ sending any bounded region $\mathcal{O}$ of Minkowski spacetime M to the local algebra $\mathcal{R}(\mathcal{O})$ defined on the underlying Hilbert space $\mathcal{H}$ containing all the observables one can measure within the corresponding region. Any observable $A \in \mathcal{R}(\mathcal{O})$ is said to be a local observable localized in $\mathcal{O}$. This grounds the possibility to introduce an alternative localization scheme: accordingly, a "click" in a particle detector within an arbitrarily small spacetime region is modeled by some local observable belonging to the corresponding local algebra. The standard axioms of Algebraic Quantum Field Theory are presented in Haag (1992). Here, we just note that they guarantee that the local algebras $\mathcal{R}(\mathcal{O})$ are von Neumann algebras and that the inductive limit of the net of all local algebras is given by the quasi-local C*-algebra $\mathcal{R} = \overline{\{\mathcal{R}(\mathcal{O}) | \mathcal{O} \subset M\}}$. In particular, the vacuum state is represented by the normalized vector Ω, which is the unique Poincaré invariant vector-state.

The condition of relativistic causality assumed in the no-go theorems against particle localizability is captured by the axiom of microcausality. For simplicity, let us refer to diamond regions: specifically, a double cone $\mathcal{O}$ in M satisfies the diamond axiom just in case the local algebra associated with its causal complement $\mathcal{O}'$ is equal to the commutant of its local algebra, i.e. $\mathcal{R}(\mathcal{O}') = \mathcal{R}(\mathcal{O})'$. Microcausality requires that any local observable in $\mathcal{R}(\mathcal{O})$ commutes with all the local observables in $\mathcal{R}(\mathcal{O}')$. The physical idea here is that it assures that measurements of observables localized in region $\mathcal{O}$ do not disturb measurements of observables localized in its causal complement $\mathcal{O}'$. The justification for regarding microcausality as an expression of relativistic causality is given in terms of the constraint of no superluminal signalling. Since $\mathcal{O}$ and $\mathcal{O}'$ are spacelike separated, a measurement performed in the former region ought not to cause an instantaneous change of the expectation value of any observable localized in the latter region, regardless of what the state of the system is. This idea can be made precise by means of the Lüders rule describing quantum-mechanical measurements. A generalized Lüders rule for effects has been formulated by Busch and Singh (1998) and Busch (1999), where an effect is any positive observable C whose expectation value $\langle \psi | C\psi \rangle$ lies in $[0, 1]$ for every unit vector ψ, so that $\| C \| \leq 1$ (see Kraus, 1983 for a review). On contrary to projections, effects allow one to account even for measurements with unsharp outcomes. In its simplest form the measurement of an effect C can be represented by the operation

$$T_C(\cdot) = C^{1/2}(\cdot)C^{1/2} + (I-C)^{1/2}(\cdot)(I-C)^{1/2} \tag{1}$$

It can be shown that, just in case microcausality holds, if C belongs to $\mathcal{R}(\mathcal{O})$ the thus-defined operation T_C acts as the identity in $\mathcal{R}(\mathcal{O}')$, thereby leaving invariant all observables localized in the causal complement of $\mathcal{O}$. As a consequence, T_C does not change the expectation value of any observable A in $\mathcal{R}(\mathcal{O}')$, that is $\langle \psi | A\psi \rangle = \langle \psi | T_C(A)\psi \rangle$ for every vector-state $\psi \in \mathcal{H}$. Accordingly, a measurement of C does not have non-local effects in $\mathcal{O}'$. That yields a version of the no-superluminal-signalling theorem in Algebraic Quantum Field Theory, whereby a signal is enacted by the Lüders rule (1). Failure to comply with such a requirement would thus result in a violation of no faster-than-light signaling. Let us emphasize that this would also entail the presence of *act–outcome correlations* across the field systems within the region $\mathcal{O}$ and its causal complement $\mathcal{O}'$. The notion of act–outcome correlations has been widely discussed in the philosophical literature on quantum non-locality. Indeed, Shimony (1986) associated it with a violation of the condition of parameter independence in the decomposition of Bell-type locality, thereby leading to a conflict with the constraint of relativistic causality.

Although the concept of localization of observables in spacetime regions is compatible with microcausality, from the axioms of Algebraic Quantum Field Theory one can derive a theorem that poses a threat for particle localizability. That is the Reeh–Schlieder theorem (1961): accordingly, for all regions $\mathcal{O}$ in Minkowski spacetime M, any vector-state of bounded energy, such as the vacuum Ω, is cyclic for the local algebras $\mathcal{R}(\mathcal{O})$. The vacuum being cyclic means that, for every vector $\psi \in \mathcal{H}$, there exists a sequence of observables $\{F_n\}_{n \in N}$ in $\mathcal{R}(\mathcal{O})$ such that

$$\| \psi - F_n \Omega \| \longrightarrow 0 \tag{2}$$

when n goes to infinity. In other words, one is able to approximate in norm any vector-state by acting on the vacuum with observables localized in the bounded region $\mathcal{O}$. In particular, one could generate a state which looks within the causal complement $\mathcal{O}'$ very different from Ω. Whether it entails a violation of relativistic causality is an outstanding issue in philosophy of physics (see Valente, 2014 for a recent discussion). However, as Fleming and Butterfield (1999) observed, "that is certainly hard to square with naive, or even educated, intuitions about localization!" (p. 159). In fact, Redhead (1995) showed that, owing to the Reeh–Schlieder theorem, one can never determine whether the system is in an N-particle state since the corresponding projection operator cannot belong to any local algebra.[1]

There is also another crucial reason why the Reeh–Schlieder theorem would undermine the intended localization scheme in Algebraic Quantum Field Theory. A necessary condition for a particle ontology is that one cannot detect any particle in the vacuum. Thus, the expectation value of a putative observable C designed to model a particle detection must be zero in the vacuum. Let us refer to it as the following:

Condition (I): $\langle \Omega | C\Omega \rangle = 0$

Yet, in conjunction with microcausality, the Reeh–Schlieder theorem entails the corollary that the vacuum is a separating vector for any local algebra associated with a region with non-empty causal complement. It means that, if $\mathcal{O}' \neq \varnothing$, then for all $C \in \mathcal{R}(\mathcal{O})$ one has $C\,\Omega = 0$ just in case $C = 0$. It follows that the expectation value of any non-trivial observable C localized in

[1] Actually, the proof of Redhead's result appeals also to the fact that all projections in the local algebras, being type III factors von Neumann algebras, are infinite. Since it is not relevant to our discussion, due to length constraints, we do not introduce this notion here.

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