ARTICLE IN PRESS

Studies in History and Philosophy of Modern Physics xxx (2017) 1–13

Contents lists available at ScienceDirect

Studies in History and Philosophy of Modern Physics

journal homepage: www.elsevier.com/locate/shpsb

Are field quanta real objects? Some remarks on the ontology of quantum field theory

Tomasz Bigaj

Institute of Philosophy, University of Warsaw, ul. Krakowskie Przedmiescie 3, 00-047 Warsaw, Poland

ARTICLE INFO

Article history:
Received 16 April 2017
Received in revised form
29 June 2017
Accepted 9 August 2017
Available online xxx

Keywords:
Quantum field theory
Fock space
Harmonic oscillators
Field quantization
Particles
Ontology

ABSTRACT

One of the key philosophical questions regarding quantum field theory is whether it should be given a particle or field interpretation. The particle interpretation of QFT is commonly viewed as being undermined by the well-known no-go results, such as the Malament, Reeh-Schlieder and Hegerfeldt theorems. These theorems all focus on the localizability problem within the relativistic framework. In this paper I would like to go back to the basics and ask the simple-minded question of how the notion of quanta appears in the standard procedure of field quantization, starting with the elementary case of the finite numbers of harmonic oscillators, and proceeding to the more realistic scenario of continuous fields with infinitely many degrees of freedom. I will try to argue that the way the standard formalism introduces the talk of field quanta does not justify treating them as particle-like objects with well-defined properties.

1. Introduction: against the particle interpretation of QFT

Quantum field theory (QFT) is to date the most successful theory of matter and its interactions at the fundamental level. Historically, QFT appeared on the scene as one way of extending non-relativistic quantum mechanics in response to certain shortcomings and limitations of the latter. One particular problem that the early quantum physicists grappled with was how to properly describe the processes of absorption and emissions of electromagnetic energy by atoms.[1] An adequate analysis of these phenomena requires that we have a theory that is both relativistic (since photons travel at the speed of light) and capable of providing a quantum description of classical fields (since absorption and emission involve electromagnetic fields and their interaction with matter). QFT aimed to satisfy these two demands. Famously, the second postulate was fulfilled by adopting the now standard procedure known as field quantization. The first undeniable success of the QFT program and its method of quantization was the development of a quantum theory of electromagnetism, called quantum electrodynamics (QED). Subsequent applications of the mathematical formalism of QFT yielded theories of weak and strong (nuclear) interactions (Yang-Mills gauge theories, Glashow-Salam-Weinberg theory of electroweak interactions, and quantum chromodynamics). In spite of its mounting conceptual and technical difficulties, of which the problem with infinities and various renormalization techniques is but one example, QFT is still considered the best working theory of fundamental interactions there is.

From a philosophical perspective, one of the most pressing questions regarding QFT is the question of what exactly it tells us about the nature of the constituent elements of reality. What is the proper ontological interpretation of QFT? As its name and origins clearly suggest, the theory seems to deal primarily with various fields (electromagnetic, strong, weak), hence an immediate conclusion may be that according to QFT the most fundamental physical entities are fields. And yet the procedure of field quantization, which is an indispensable part of QFT, results in a "particularization" or "discretization" of fields in the form of interaction carriers (photons, gluons, gauge bosons). Thus it may be surmised that the basic lesson from QFT is that ultimately there are only particles and void. For many working physicists, as well as some philosophers, it is an unquestionable truism that QFT deals primarily with particles. In support of this claim we can recall the historical development of the concept of quanta from an ad hoc hypothesis postulated by Planck in order to solve the problem of black body radiation to the corpuscular interpretation of electromagnetic radiation advanced by Einstein and confirmed in

E-mail address: t.f.bigaj@uw.edu.pl.

[1] See (Kuhlmann, 2010, pp. 27–31) for an overview of this historical episode. Other, more comprehensive historical introductions to QFT can be found in (Cao, 1997) and (Auyang, 1995).

http://dx.doi.org/10.1016/j.shpsb.2017.08.001
1355-2198/

Please cite this article in press as: Bigaj, T., Are field quanta real objects? Some remarks on the ontology of quantum field theory, Studies in History and Philosophy of Modern Physics (2017), http://dx.doi.org/10.1016/j.shpsb.2017.08.001

experiments (photoelectric effect, Compton scattering). Moreover, it may be pointed out that QFT is a theoretical frame in which the Standard Model is formulated, and the Standard Model is cashed out in terms of elementary particles and their interactions. Simplifying things a bit, we may be tempted to say that because QFT applies to objects such as electrons, photons, gluons and the like, and because these objects are commonly referred to as "particles", ontologically speaking QFT is a theory of particles.

However, the argument "from scientific practice" for the particle interpretation of QFT is very weak. The fact that physicists label certain elements described by their theories "particles" does not imply that from an ontological point of view these elements indeed deserve to be categorized as such. For all we know, electrons may turn out to be some aspects or manifestations ("epiphenomena") of an underlying entity, which may be fundamentally non-particle-like. As a matter of fact, even the founders of QFT were not unanimous in their opinions regarding the proper ontological interpretation of this theory. For instance, Schrödinger maintained that fundamental physical reality consists of waves only, whereas so-called "particles" should be rejected, since they lack features such as identifiability over time or distinguishability. Other physicists were more sympathetic towards the standard concept of a particle though. When in 1927 Dirac introduced the procedure of field quantization and applied it to the case of electromagnetic radiation, he interpreted it as showing conclusively that light quanta are independent, fundamental substances, while the wave function is a mere calculational device with no deeper ontological meaning. However, Dirac's argument can be questioned. As Cao (1997, pp. 160–165) observes, Dirac's reasoning is based on the confusion of "second quantization" (quantization of the wave function of a system of particles) with "field quantization" (quantization of a real, physical field, such as the electromagnetic field). The philosophical controversy between the particle and field interpretations of QFT continues to this day, with numerous arguments presented both for and against each of these two rival conceptions. In what follows we will briefly discuss some of the best-known arguments against the particle interpretation of QFT.

A prominent group of arguments of this type are based on several no-go results provable in some variants of QFT. These results typically show that certain common-sense conditions that we usually associate with the concept of particles, such as the assumption of localizability, cannot be jointly satisfied within the broad framework of QFT. To begin with, we have Malament's theorem, which is not associated with any concrete variant of QFT but instead proceeds from some general assumptions that should be satisfied in all relativistic quantum theories of localizable particles, and yet can be shown to lead to a contradiction.[2] These assumptions are: localizability, microcausality, translation covariance, and the assumption that the energy is bounded from below. Localizability prescribes that the probability of finding an object simultaneously in two disjoint regions should be zero (perhaps this postulate could be alternatively and more appropriately labeled "no-bilocation"). Mathematically, this condition is expressed in the requirement that projectors representing propositions of the form "a particle is localized in a given region" should be orthogonal if these regions are disjoint subsets of a hyperplane of simultaneity. Microcausality, in turn, encompasses the relativistic intuition that detection measurements performed in one region cannot instantaneously affect the statistics of detection measurements in a distant region. This can be spelled out in the form of the condition that for two disjoint regions Δ and Δ' on a hyperplane of simultaneity there is a time interval ε such that if we performed a time-like translation on region Δ' by an amount t smaller than ε, then projectors E_Δ and $E_{\Delta'+t}$ corresponding to appropriate regions should commute. Finally, translation covariance means that translations of the underlying spacetime are represented by a continuous group of unitary operators in the sense that applying a translation a to a region Δ is equivalent to applying the corresponding unitary operator $U(a)$ to the projector E_Δ.

A closely related result is known under the name of Hegerfeldt's theorem.[3] In addition to the energy bounded below and the time-translation covariance from Malament's theorem, it formulates two new conditions that replace localizability and microcausality: monotonicity and no instantaneous wave spreading. Monotonicity asserts that if we have a nested family of subsets of an element of a foliation of spacetime, and the intersection of this family gives region Δ, then the intersection of corresponding projectors should give E_Δ. The most significant premise of the theorem states that if a particle is localized at a given moment in region Δ, then for any region Δ' such that $\Delta \subseteq \Delta'$ (with the assumption that the boundaries of Δ and Δ' are separated by a finite distance) there is an interval ε such that for all time-like translations t smaller than ε it is certain that the particle can't be found outside the translated region $\Delta' + t$ (the projector E_Δ is included in the projector $E_{\Delta'+t}$). The theorem proves that given these assumptions it follows that any arbitrary time-like translation of E_Δ gives back E_Δ, which means that the particle will forever stay in the same region. By transposition, if any movement of the particle is possible at all, it must be in the form of an instantaneous spreading violating the principles of relativity.

Both theorems sketched above show that within QFT there is a serious problem with the concept of a localizable particle obeying the principles of relativity. However, it is open to debate whether this fact shows the untenability of the particle interpretation of QFT,[4] or rather that any quantum theory is ultimately at odds with some fundamental relativistic intuitions (and, therefore, we have yet to come up with a new theory that could successfully incorporate both quantum and relativistic aspects of reality, for instance quantum gravity). But the list of arguments against the particle interpretation of quanta is not exhausted yet. Another key result is known as the Reeh-Schlieder theorem, provable within so-called algebraic quantum field theory (AQFT). Algebraic QFT is a mathematical approach based on the assumption that each spatiotemporal region is associated with an algebra of operators representing possible measurements within this region.[5] AQFT is usually presented in the form of several mathematical axioms (and thus the acronym AQFT is alternatively expanded as axiomatic quantum field theory), of which the axiom of locality is the most recognizable from the physical point of view. Locality, also known as causality, asserts that observables associated with space-like separated regions commute (more precisely, that their commutators in the case of bosons and the anti-commutators in the case of fermions are zero). It is also assumed that the algebra of operators associated with a subset of a given region O is included in the algebra corresponding to O (isotony). Another important axiom ensures the existence of a unique state that is invariant under all Poincaré transformations. This state is known as the physical vacuum.

[2] See (Malament, 1996). The brief presentation of Malament's theorem given above is based on (Halvorson & Clifton, 2002).

[3] See (Hegerfeldt, 1974, 1998). Again, we will be following Halvorson and Clifton (2002) in the exposition of the theorem.

[4] In their analysis of the consequences of Malament's theorem, Fleming and Butterfield (1999) argue that the failure of the assumption of microcausality can be reconciled with the principles of relativity. For an extensive response to this strategy of defending the notion of localizable particles in QFT see (Halvorson, 2001).

[5] See (Haag, 1996) for an introduction to AQFT.

Please cite this article in press as: Bigaj, T., Are field quanta real objects? Some remarks on the ontology of quantum field theory, Studies in History and Philosophy of Modern Physics (2017), http://dx.doi.org/10.1016/j.shpsb.2017.08.001