Studies in History and Philosophy of Modern Physics 60 (2017) 46–80

Contents lists available at ScienceDirect

Studies in History and Philosophy of Modern Physics

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

The state is not abolished, it withers away: How quantum field theory became a theory of scattering

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A R T I C L E I N F O

Article history:
Received 27 September 2016
Accepted 19 January 2017
Available online 24 February 2017

1. Introduction

1. Introduction Learning quantum field theory (QFT) for the first time, after first learning quantum mechanics (QM), one is (or maybe, rather, I was) struck by the change of emphasis: The notion of the quantum state, which plays such an essential role in QM, from the stationary states of the Bohr atom, over the Schrödinger equation to the interpretation debates over measurement and collapse, seems to fade from view when doing QFT. Not that it's gone – as any physicist will be quick to tell you, QFT is simply a quantum theory, with all the general structure of QM taken over unchanged. But the quantum state is hardly mentioned, when dealing with Feynman diagrams, path integrals and all the other mainstays of an introductory QFT course.

This was not always so: The QFT of the late 1920s and 1930s developed as a straightforward extension and generalization of QM, and consequently writing down Schrödinger equations and calculating the energies of stationary states were the prime concerns of the physicists working with QFT at the time.[1] But, as is well-known, this early QFT suffered from crippling defects, most notably the divergence problem, i.e., that all calculations appeared to give nonsensical, infinite results, once one went past the first approximation. The divergence difficulties of QFT (or at least of quantum electrodynamics) were solved through the renormalization techniques developed in the late 1940s. As was frequently stressed already at the time, the success of the renormalization program meant that the conceptual foundations of QM could be taken over to field theory with only slight modifications, as opposed to what physicists had generally believed all through the 1930s and early 1940s. But even though the foundations did not change (or change only just enough so that they could stay the same, as Weinberg has characterized this development (Weinberg, 1977, p.18)), the formalism of renormalized QFT (finding its first definitive formulation in Freeman Dyson's systematization of Richard Feynman's modular diagrammatic approach) looked quite different from that of 1930s QFT and a lot more like what we call QFT today.

What we observe can be called a paradigm shift. The term "paradigm shift" can be used in two ways, to designate a change of worldview and conceptual foundation or to designate a change in the paradigmatic problem to be calculated from the theoretical foundations. Oftentimes these two changes occur simultaneously and a distinction need not be made. Our case is different: Although the theoretical basis remained almost the same, the paradigmatic problem that was to be calculated from this basis changed. QM had been all about properties of the quantum state, most importantly the associated energy levels. QFT was all about scattering. Both frameworks were of course able to address other problems, but the calculations were in general modeled after the paradigmatic calculation: So, in QM, scattering was traditionally modeled as a stationary state, assuming a continuous influx of scattered particles.[2] Conversely, bound-state problems could be treated in renormalized QFT using Feynman graphs, whose mere design was a constant reminder of their origins in the calculation of scattering matrix elements.

This shift of emphasis is certainly not ignored in the Sam Schweber's major work on the re-invention of QED in the late 1940s (Schweber, 1994), but it is merely alluded to at several points and not analyzed or identified in greater detail. It is clearly emphasized and discussed explicitly by Wüthrich (2010). Both books serve as an invaluable foundation for the research presented here. But also in the latter study, the transition is looked at only very locally, both in space and time (Feynman's study of the Dirac equation in the years 1946-1949) and in "conceptual space" (the modes of representation and the shift from spectroscopic term schemes to Feynman diagrams).

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[1] One just needs to look at the first paper on the full theory of quantum electrodynamics (Heisenberg & Pauli, 1929).

[2] See, e.g., the standard textbook by Dirac (1935, Section 9).

https://doi.org/10.1016/j.shpsb.2017.01.004
1355-2198/

In this paper, I attempt to give a broader reconstruction of how this paradigm shift came about. I will attempt to identify several distinct historical developments that contributed to it and to identify several different factors that were essential for the possibility and the actual occurrence of this shift. For the organization of this paper, I have opted for a focus on the former, i.e., on a more narrative, rather than a thematic, structure. To counterbalance this, I will begin by briefly presenting the major recurring themes that the reader should look out for in the following (double) narrative.

The first impetus towards this paradigm shift, which therefore shows up as a starting point in several of the narrative threads below, is the attempt to formulate quantum theory in a more explicitly relativistic manner. The great champion of these attempts is Paul Dirac, who throughout the 1930s provided various starting points for such an explicitly relativistic formulation of quantum theory. What all these formulations had in common was that in some sense they problematized the quantum mechanical notion of an instantaneous state and tended towards replacing it with a focus on overall processes. This stemmed from the relativistic need to treat space and time on the same footing and the consequent tendency of relativity towards a block universe view.

Such attempts at making quantum theory more relativistic would hardly have been necessary if there hadn't been the grave divergence difficulties of QFT. For Dirac and others the relativistic reformulations were just preliminary exercises for a successor theory to QFT, which would circumvent the divergence difficulties and provide a consistent and divergence-free quantum theory of electrodynamic (and nuclear) interactions. Two radical attempts at creating such an entirely new theory in the 1930s and 1940s play an important role in my reconstruction: Heisenberg's S-Matrix theory and the Wheeler-Feynman theory of action-at-a-distance electrodynamics. I have accordingly structured my narrative along these two attempts, how they arose and how they influenced the formulation of renormalized QFT. For while they eventually were generally viewed as having gone way too far – demanding a total overhaul of the foundations of the theory, when in fact small, conservative modifications were all that was needed in order to construct a workable QFT – they provided essential insights and methods integrated into the new scattering-focused formalism.

The two approaches I will be studying were very different, but they shared one central aspect: In attempting to solve the difficulties of QFT, they got rid of the notion of a (quantum) state altogether. The framework they provided for such a theory was taken over into "regular" QFT in the late 1940s, and defined that theory in an essential way, by providing calculational techniques and, perhaps even more importantly, by preparing a mindset in which scattering could be thought of as the primary, paradigmatic thing to be calculated from a theory. They thus paved the way for the marginalization of the quantum state, even if it turned out that it would not entirely be abolished, as had been the original expectation.

This paper has a clear focus on theoretical and conceptual developments, but experimental developments played an important role, which will also be duly addressed. In particular, the growing importance of scattering experiments in cosmic ray physics was essential for Heisenberg's path to the S-Matrix approach. But the role played by experiments is more complex than that. In Feynman's approach, they initially hardly played a role, as his was merely an attempt to reconstruct the well-established results of electrodynamics in a theory without instantaneous states (and without localized fields). Also, the experimental developments that led up to the development of renormalized QED were not scattering experiments. In particular, the Lamb Shift was really a classical spectroscopic measurement, similar to the spectroscopic experiments that had played such a central role in the development of Bohr's theory of the atom and the consequent conceptualization of quantum theory as a theory of stationary states and transitions between them. What we will thus encounter several times in the following narrative is the difficulty of adapting the newly emerging scattering theories to the calculation of traditional quantum theory observables, such as the energies of stationary states. The partial successes in this direction played an important role in the establishment of the scattering paradigm.

I now turn to my two central narratives: In the first half of the paper, I will describe the genesis and initial success of Heisenberg's S-Matrix theory, culminating in Stueckelberg's theory of the causal S-Matrix, which might have been the starting point for the establishment of a scattering-centric reformulation of QFT, if it hadn't been for Feynman's modular diagrammatic approach appearing at the same time. The development of this latter approach is recounted in the second half of the paper, beginning from Wheeler and Feynman's attempts to reformulate electrodynamics without fields and Feynman's attempts to quantize such a theory using path integrals. The second half concludes with Dyson's merging of Heisenberg's S-Matrix approach with Feynman's techniques to create the new formulation of QFT and thereby conclude the paradigm shift from energy levels to scattering.

2. The S-Matrix

Heisenberg's theory of the S-Matrix was laid out in a series of papers published during World War II. But we will go back somewhat further and study the origins of this theory in Heisenberg's attempts at incorporating a smallest, fundamental length into quantum theory. The fact that Heisenberg's S-Matrix has its origins in his theory of the fundamental length has often been remarked. In the following, I will be discussing this development specifically with an eye to the abolishment of the quantum state.

2.1. Heisenberg and the fundamental length

The development of Heisenberg's work on a fundamental length is described in (Kragh, 1995). The important point for our purposes is that initially the fundamental length was intended solely to remove the divergence difficulties of QED, acting as a cutoff scale for the divergent integrals appearing in higher order calculations in perturbation theory. The fundamental length was introduced into the theory by modifying the Hamiltonian, first by replacing differentials by differences (the 1930 lattice world, discussed in detail in (Carazza & Kragh, 1995)), later by smearing out the energy density at a point in space with the help of a regularizing function (the 1935 Δ-formalism, discussed in (Miller, 1994)). These attempts always implied absolute limits on position measurements (or the measurements of field strengths at a point in space), but did not alter the general structure of the fundamental dynamical equations, holding on to Hamiltonians and wave functions. These attempts did not go very far, running afoul, e.g., of their lack of relativistic invariance, and neither of them was ever published.

In 1936, Heisenberg turned to Fermi's theory of β decay, which implicitly contained a parameter with the units of a length in the form of the dimensionful coupling constant g. Initially, Heisenberg's interest in Fermi theory (as laid out in a letter to Pauli on 26 May 1936)[3] was not related to the divergence difficulties. Instead, he

[3] All letters from and to Pauli in the 1930s are reproduced in (Hermann, von Meyenn, & Weisskopf, 1985). All translations are by me.