Philosophical Issues in Quantum Field Theory

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Outline

1. Introduction: What Is Quantum Field Theory and Why Do We Need It?
2. The Ontology of Quantum Field Theory: Quanta, Fields, or Something Else?
3. The Methodological Debate: Which Quantum Field Theory Should Philosophers Study?

Why Is Quantum Mechanics Not Enough?

- Quantum mechanics (QM) is non-relativistic. We want a theory that unifies quantum mechanics with special relativity.
- QM describes systems with a fixed number of particles. We want to describe creation and annihilation of particles.
- Fields are described classically in QM:

  $$i\hbar\frac{\partial}{\partial t}\psi(\boldsymbol{r},t) = \left(-\frac{\hbar^2}{2m}\nabla^2 + V(\boldsymbol{r})\right)\psi(\boldsymbol{r},t)$$

  We want a theory which describes particles and fields in a quantum fashion.
- More generally: we want to describe systems having infinitely many degrees of freedom.

From QM to Quantum Field Theory (QFT)

In 1-particle QM, states are described by vectors $|\psi\rangle \in \mathcal{H}$.
For *n*-particle systems, build tensor products:
$|\psi\rangle \otimes \ldots \otimes |\phi\rangle \in \mathcal{H}_1 \otimes \ldots \otimes \mathcal{H}_n$

Problems with this formalism:

1. Not appropriate for describing particle creation and annihilation: when *n* changes, a different Hilbert space is required.
2. The labels 1,. . . , *n* suggest that the particles are individuals, which is problematic in quantum theories.
   (For more on identity and individuality in quantum theory, see pp. 8–9 of the course booklet.)

Better Idea: instead of labeling particles, label the states.

Example (description of a 3-particle state)

$|\psi\rangle \otimes |\chi\rangle \otimes |\chi\rangle \in \mathcal{H}_1 \otimes \mathcal{H}_2 \otimes \mathcal{H}_3$ becomes $|1_\psi, 2_\chi, 0_\phi, \ldots\rangle$
(or, more simply: $|1, 2, 0, \ldots\rangle$).

The Fock Space Representation of QFT

Definition

The vector space spanned by all the vectors $|n_\psi, n_\chi, \dots\rangle$ is called Fock space $\mathcal{F}$.
For bosons, $n_i \in \mathbb{N}_0$, for fermions, $n_i \in \{0, 1\}$.

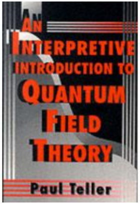
The new formalism solves the problems mentioned above:

1. Creation and annihilation are easily accommodated, e.g.: annihilation of a particle in state χ turns $|1, 2, 0, \dots\rangle \in \mathcal{F}$ into $|1, 1, 0, \dots\rangle$, which is still in $\mathcal{F}$.
2. It is clear that permutation of identical particles makes no difference: while the old formalism distinguished between $|\psi\rangle \otimes |\chi\rangle \otimes |\chi\rangle$ and $|\chi\rangle \otimes |\psi\rangle \otimes |\chi\rangle$, the new formalism describes both states with $|1, 2, 0, \dots\rangle$.

The Quanta Interpretation of QFT

Standard view among physicists:

> *Realizing that the energy in a quantized field comes in quantized energy packages, which in all respects behave like elementary particles, and, conversely, realizing that operators in the form of fields could be defined also when one starts up with Hilbert spaces consisting of elementary particles, it was discovered that quantized fields do indeed describe subatomic particles. ('t Hooft 2007, 662)**



Definition

Quanta are particles without individuality. They can be *counted*, but not *numbered*.

Introduction to a quanta interpretation of QFT: Teller (1995).

* All references can be found on pp. 10–11 of the course booklet, unless otherwise stated.

Problems for the Quanta Interpretation

1. Superposition of states in $\mathcal{F}$: How many quanta does a state like $\alpha|1,0,\ldots\rangle+\beta|2,0,\ldots\rangle$ contain?
2. The vacuum state $|0,0,\ldots\rangle\equiv|0\rangle$ has non-vanishing expectation values for some properties. → properties of what?
3. Unruh effect: an accelerated observer detects a thermal bath of (Rindler) quanta where an inertial observer detects a vacuum.
4. Theoretical results against localizability: Reeh-Schlieder theorem, no-go theorems by Malament and Hegerfeldt
5. Haag's theorem: interacting fields do not allow a Fock-space representation, and therefore no quanta interpretation.

A Closer Look at Problem #5: QFT with Interactions

Representation of time evolution in quantum theories

Schrödinger picture State evolution of a system is governed by a Hamilton operator H; operators are stationary.

Heisenberg picture States are stationary; operators evolve according to H.

Interaction picture $H = H_0 + H_I$, with H_I governing the evolution of states, H_0 the evolution of operators.

The Fock representation is defined for free fields ($H = H_0$). If we do the same for interacting fields ($H = H_0 + H_I$), Haag's theorem implies $H|0\rangle = \infty$ (unphysical vacuum state, hence no quanta interpretation).

See also Fraser, D. (2008): The fate of 'particles' in quantum field theories with interactions. *Studies in History and Philosophy of Modern Physics 39*, 841–859.

QFT without Quanta

Problems for interpreting QFT in terms of fields:

1. Unlike classical fields, quantum fields $\hat{\phi}(\boldsymbol{x}, t)$ do not assign physical values to space-time points.
   - Teller (1995, 99): The operator associated with a given space-time point "corresponds not to the value of some physical quantity but to the full spectrum of values of some quantity, which value being applicable being determined by the state that happens to obtain."
   - Teller (2002): The quantum field permits only structural, not causal explanation.
2. Baker (2009): Some of the problems affecting quanta interpretations are equally damaging to field interpretations.

Some other proposals for an ontology of QFT: events, properties (tropes), structures,...

How Can Fock Space QFT Describe Interactions?

General aim: describe the temporal evolution of the system's state $|\psi\rangle$ by finding the evolution operator U, defined by
$|\psi(t)\rangle = U(t, t_0)|\psi(t_0)\rangle$
(U is connected to H as follows: $U(t, t_0) = e^{-iH(t-t_0)}$)

The basic idea of scattering theory

In $H = H_0 + H_I$, regard H_I as a small perturbation of H_0. Then U can be calculated (approximately) as a perturbation series:

$$U(t, t_0) = 1 + \sum_{n=1}^{\infty} (-i)^n \int_{t_0}^{t} dt_1 \int_{t_0}^{t_1} dt_2 \cdots \int_{t_0}^{t_{n-1}} dt_n H_I(t_1) \cdots H_I(t_n)$$

Assumption: For $t_0 \to -\infty$ and $t \to \infty$, the interaction H_I vanishes. Then, in- and out-states are free states, allowing a Fock representation. The scattering operator $U(\infty, -\infty)$ describes the transformation from in-state to out-state.

Conventional QFT vs. Axiomatic QFT

Problem: the perturbation series is not well-defined, because it contains divergent integrals. However, thanks to various renormalization techniques, QFT is extremely successful in describing scattering experiments.

Opposing views concerning renormalization

1. Since renormalization is not based on rigorous axioms, conventional (also called ‘Lagrangian’) QFT is not a proper theory. Philosophers interested in conceptual issues should instead consider axiomatic (or ‘algebraic’) QFT (Kuhlmann 2010, Fraser 2009).
2. Renormalization is nowadays well-understood, so CQFT is a proper object of conceptual considerations. And it is empirically much more successful than AQFT (Wallace 2006).

A Case of Underdetermination?

The rivalry between CQFT and AQFT can be seen as a case of underdetermination of theory by evidence.
(See the recent papers by Wallace and Fraser in *Studies in History and Philosophy of Modern Physics, 42* (2011), 116–135.)

Points of debate:

1. Is it a genuine case of underdetermination, given that AQFT can not (yet?) describe realistic interactions, i.e., reproduce the standard model of particle physics?
2. Are CQFT and AQFT really different theories? They seem to differ only on very small lengthscales, which might be irrelevant:

   > *Whatever our sub-Planckian physics looks like . . . there are pretty powerful reasons not to expect it to look like quantum field theory on a classical background spacetime. As such, what QFT (of any variety) says about the nature of the world on lengthscales below* $\sim 10^{-43}$ *m . . . doesn't actually tell us anything about reality (Wallace 2011, 120–1).*