Physics Underdetermines Metaphysics: The case of AQFT

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Contents

A brief overview of AQFT

- The fundamental idea of AQFT is to consider that the physical content of a system described by AQFT is not encoded in an individual algebra of observables but rather in the *mapping* $O \to A(O)$ from regions O of Minkowski space-time to *algebras of local observables* $A(O)$.

- This mapping informs us on which observables are localized and then take value in O.

A brief overview of AQFT – Axioms 1-2

According to the Haag-Kastler formulation, the net of local algebras has to satisfy four axioms:

(1) Isotony: the mapping $O \rightarrow A(O)$ is an inductive system. This means that an observable measuralbe in the region of space-time O_1 is measurable also in a region of space-time O_2 containing O_1.

(2) Microcausality: if O_1 and O_2 are space-like separated space-time regions, then $[A(O_1), A(O_2)] = \{0\}$. That is, all observables connected with a space-time region O_1 are required to commute with all observables of another algebra which is associated with a space-like separated space-time region O_2.

A brief overview of AQFT – Axioms 3-4

(3) Translation covariance: if A is a net of local algebras of observables on an affine space, it is assumed that there exists a faithful and continuous representation $x \rightarrow \alpha_x$ of the translation group in the group of Aut$A$ of automorphisms of A and $\alpha_x(A(O)) = A(O + x)$, for any space-time region O and translation x.

(4) Spectrum condition: the support of the spectral measure of the operator associated with a translation is contained in the closed forward light-cone, for all translations. This ensure that negative energies cannot occur.

A brief overview of AQFT – Representations of the algebra

- In the specific context of AQFT, a *representation* is a *map* that associates every element of an abstract C^*-algebra A (in which the theory is formulated) with the set of all bounded operators acting on an Hilbert space H.
- A representation is *irreducible* if the representation space H has no closed invariant subspaces.
- The resulting Hilbert space H is then called the *representation space*.

A brief overview of AQFT – Inequivalent irreducible representations

- One of the first results of AQFT is the the acknowledgement of the emergence of many *inequivalent irreducible representations* of the same algebra of observables generated by the CCRs.

- In QM, the *Stone-von Neumann uniqueness theorem* proves that the algebra generated by the CCRs for the position and momentum operators has a representation of these two set of operators in Hilbert space up to unitary equivalence suffices to describe a certain physical system.

- However, this theorem fail to hold in the context of AQFT. (The theorem is in fact proved only for system with a finite number of degrees of freedom.)

An ontology for AQFT: Particles or Fields? - Particles

- A particle should be a *countable* and *localizable entity*

- Against *countability*:

  Haag's theorem

  Reeh-Schlieder theorem

- Against *localizability*:

  Reeh-Schlieder theorem

  Malament theorem

- Moreover, the **Unruh effect** seems to show that the physical content of a system described by AQFT is *representation-dependent*

An ontology for AQFT: Particles or Fields? - Particles

- **Haag's theorem** proves that the Fock space representation available for non-interacting physical systems cannot be also used in the case of interacting physical systems.
- However, the total number operator – representing the number of particles in a physical system – may be precisely defined only in a Fock space representing non-interacting physical systems.
- Hence, *it is not possible to define a total number operator for interacting AQFTs.*

An ontology for AQFT: Particles or Fields? - Particles

- **Reeh-Schlieder theorem** shows that for net of local algebras $O \rightarrow A(O)$ satisfying the axioms mentioned above, the vacuum representation is *cyclic* for *A(O)*. *Vacuum ciclicity* means that for any operator $A \in A(O)$, the set of states generated by $A\Omega$ is dense in H, where Ω is the vacuum state and H the Hilbert space of states.

- If a vector |ψ> has bounded energy, then it is *cyclic* for any local algebra $A(O)$.

- Corollary: If a vector |ψ> has bounded energy, then it is *separating* for any local algebra $A(O)$.

An ontology for AQFT: Particles or Fields? - Particles

"The Reeh-Schlieder theorem basically says that the action of operators associated with any bounded open spacetime region O on the vacuum state $|\Omega>$ in H_ω allows one to get arbitrarily close (in norm) to any state in H_ω ($|\Omega>$ is said to be `cyclic' for any local algebra of operators - this is true for any bounded energy state). In particular, the action on the vacuum of operators localized in O, which can be arbitrarily small, can generate (in the above sense) any state departing arbitrarily from the vacuum for regions that are space-like separated from O. Most importantly, this surprising result finds its roots in the fact that the vacuum state is indeed a highly entangled state (Redhead 1995)."

(Lam 2013, 2-3)

An ontology for AQFT: Particles or Fields? - Particles

- Moreover, Redhead (1995) shows that the **Reeh-Schlieder theorem** also implies that *local measurements can never determine whether you are looking at an N-particle state or a vacuum state*.

- A projection operator P_Ψ (which corresponds exactly to a state Ψ of N-particles) can never be a local element of the algebra defined in the specific region of space-time O where one is performing the measurement.

An ontology for AQFT: Particles or Fields? - Particles

- **Malament's theorem** assumes four conditions that must be satisfied by a relativistic theory that aims to describe physical systems composed of particles. Among these conditions, those which are of most interest for the purpose of this section are those of *localizability* and of *locality*.

- If one accepts all the conditions proposed, it follows that *it is impossible to have a specific localization of a particle in any physical system described by relativistic AQFTs*.

An ontology for AQFT: Particles or Fields? - Particles

- The **Unruh effect** shows that an accelerated observer in a flat space-time will experience a *thermal bath* of particles (i.e., *Rindler quanta*) exactly when the quantum field in which he moves is in a vacuum state.

- In the particle interpretation of AQFT, a vacuum state is a state in which there should be no particles.

- However, *the Unruh effect seems to show that the particle content of a physical system is dependent on the motion of an observer.*

An ontology for AQFT: Particles or Fields? - Fields

- Baker (2009) proves that the *wavefunctional space* (which seems to ground a filed intepretation) and the *Fock space* used in the context of free AQFTs (which seems to ground a particle interpretation) are represented by the same *Hilbert space* up to unitary equivalence.
- Redhead (1995) suggests that the particle and the field intepretation of the physical content of a AQFT system are actually *complementary*.
- However, the unitary equivalence of these two formalisms would allow the generalization of some of the particle problems also to the quantum fields.

No particle nor fields: structural realism and AQFT

- An important feature of AQFT is the fundamental entanglement structure. **Reeh-Schlieder theorem** in fact shows that the vacuum state is highly entangled across many space-like separated regions.

- The reason is that the local algebras in AQFT are *type III von Neumann algebras*: any state in a *type III von Neumann algebra* is *intrinsically mixed* (*type III von Neumann algebras* do not contain (one-dimensional) finite abelian projectors).

- Any global state (like the vacuum state) is then entangled across any diamond or double-cone region of space-time and its causal complement.

- *The fundamental entanglement of all quantum field systems shows the relational-structural character of AQFT.*

No particle nor fields: structural realism and AQFT

Lam then suggests an ontology of *entangled structures*:

"The ontology of (algebraic approach) to RQFT [that is, relativistic quantum field theory] is an ontology of 'entangled structures', understood in the sense of networks of entanglements relations among quantum field systems whose existence – what it means for a quantum field system to be the one it is – depends on the entanglement relations they enter into (on the structure they are part of)." (Lam 2013, 8)

Superselection Formalism

- However, Lam's proposal seems to be too abstract.
- French (2012) proposes a different structuralist interpretation of AQFT gounded in the *superselection formalism*.

- The most important aim of superselection theory is to sort out all the unphysical representations.

- It is then important to formulate a superselection criterion that allows to drawn a distinction between physical and unphysical representations.

- We have two possible criteria: (i) *Doplicher, Haag, Robert (DHR)*; (ii) *Buchholz and Fredenhagen (BF)*.

Superselection Formalism

(1) First of all, the internal symmetry considered by the analysis of the superselection formalism should always be represented by gauge symmetries.

(2) Second, quantum numbers manifest themselves with the existence of superselection rules for the states over the algebra of observables.

(3) Third, the *net structure* of charge quantum numbers serves to distinguish different species of “particles” and characterize their properties.

In the context of AQFT, the most important result of a superselection analysis is then to prove the existence of a *charge structure* (in terms of *composition laws*) with an *exchange symmetry* (in terms of *statistics*) that is *encoded in the net of algebra of observables*.

Superselection Formalism

DHR show that it is possible to recover all the properties of quantum fields from the analysis of superselection sectors. In particular, they are able to recover the the following structures:

(1) *Properties of quantum number* (baryon number, lepton number, and the magnitude of generalized isospin);

(2) *Composition law* and *conjugation of charge*;

(3) *Exchange symmetry of identical charges* – that it, statistics.

Superselection Formalism

- Interestingly, DHR also proves that charge quantum number structure is in a one-to-one correspondence to the labels of (equivalence class) of irreducible representation of a compact gauge group.

- Moreover, the composition law is represented by a tensor group of representations belonging to this group.

- The charge conjugation is represented by the complex conjugate representation.

- Finally, it is possible to assign a sign to each type of charge and this allows to describe the fermionic or bosonic nature of the "particle/field system".

Superselection Formalism

- Buchholz and Fredenhagen propose a different criterion and introduce the notion of *topological charge*, in order to consider also electric charges .

- The idea is to consider *almost local algebras* and *almost local operators* in order to have an account of non-localizable charges.

- It is then possible to construct a *composition of sectors, charge conjugation* and an *exchange symmetry* analysis also in the context of the BF analysis.

- In a theory based on a Minkowski space-time, the results of such analysis are equivalent to those of the DHR analysis.

Different metaphysical options for AQFT

- The structural interpretation of AQFT based on the supeselection formalism might be formulated both in the context of at least two different metaphysics:

  (i) a **monist metaphysics** (French 2010, Schaffer 2010, and Ismael and Schaffer 2016)

  (ii) a **(quantum) holistic metaphysics** (Bhogal and Perry 2015 and Morganti and Calosi 2016).

- The choice of the correct metaphysical option is then *underdetermined* by the theory.

Different metaphysical options for AQFT

An argument in favor of a **monist metaphysics:**

(1) In a pluralist view of our physical world, there should be a *Democritean account* for entanglement relations;

(2) Such an account should be spelled out in terms of particles (or fields) *plus* entanglement relations;

(3) In AQFT, there are no particles (and no fields);

(4) Thus, we would have only entanglement relations;

(5) But, such entanglement relations are spread over all the universe;

(6) Hence, entangled systems are fundamental wholes; and since the cosmos is an entangled system, then the cosmos is a fundamental whole.

Different metaphysical options for AQFT

- On the other hand, it also possible to claim in favor of **quantum holism**, where the fundamental ontology might include *particles*, their *intrinsic properties*, and *spatio-temporal relations*, but also *entanglement relations*.
- Such a proposal does not posit a fundamental whole, but rather a *new fundamental relation among fundamental parts*.
- This proposal seems to be implementable in the case of AQFT quite easily:
- The entire *Humean mosaic* is given by the vacuum sector (which represents the whole universe), and the sub-regions are the different – but intrinsically entangled – spatio-temporal regions.

Different metaphysical options for AQFT

- Morganti and Calosi (2016) claim then that entangled systems *emerge* from the interaction between different physical systems.

- This account of *quantum composition* does not eliminate the notion of part, nor does it posit the whole as ontologically prior or fundamental.

- In this context, the quantum world can be considered as a *net of relations plus the individual quantum systems which are related by entanglement.*

- The individual quantum systems are the spatio-temporal regions, which are *intrinsically related* by the entanglement relations that were created by certain interactions that took place at a certain time in the evolution of the universe. All the spatio-temporal regions are then *relationally connected*, but without any necessary need to posit the priority of the whole, nor the reducibility of individual systems to relations.

Conclusion

- A (concrete) structural interpretation of AQFT is possible thanks to the superselection formalism.
- Superselection formalism helps to individuate the *physical representations* and then the ***physical structures***, by sorting out all the representations that have not a physical menaning.
- However, such strucural interpretation of AQFT is compatible with different metaphysical options, such as ***monism*** and ***quantum holism***.
- ***The metaphysics of AQFT is underdetermined.***

Thank you.

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