BOHMIAN-TYPE QFT AND MALAMENT NO GO THEOREM

Andrea Oldofredi 02 May 2014, Lausanne

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  - a) Single particles species, this is the disjoint union of the *n*-particle configuration space

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  - b) for several particles species, there is the Cartesian product of several copies of $\Gamma\mathcal{Q} = \bigcup_{n=0}^{\infty} \mathcal{Q}^{[n]}$, one for each species. One obtains a configuration space which is an union of sectors $\mathcal{Q}^{[n]}$ where $n = (n_1, \dots, n_\ell)$ is the ℓ-tuple of the particles number for a certain species of particles.

Ontology

E.g.:

QED $\rightarrow \mathcal{Q}$ is a product of 3 copies of

$$\Gamma\mathcal{Q} = \bigcup_{n=0}^{\infty} \mathcal{Q}^{[n]}$$

Particles species involved: electrons, positrons and photons;

In this case, a configuration space specifies *number* and *position* of all e^-, e^+, γ.

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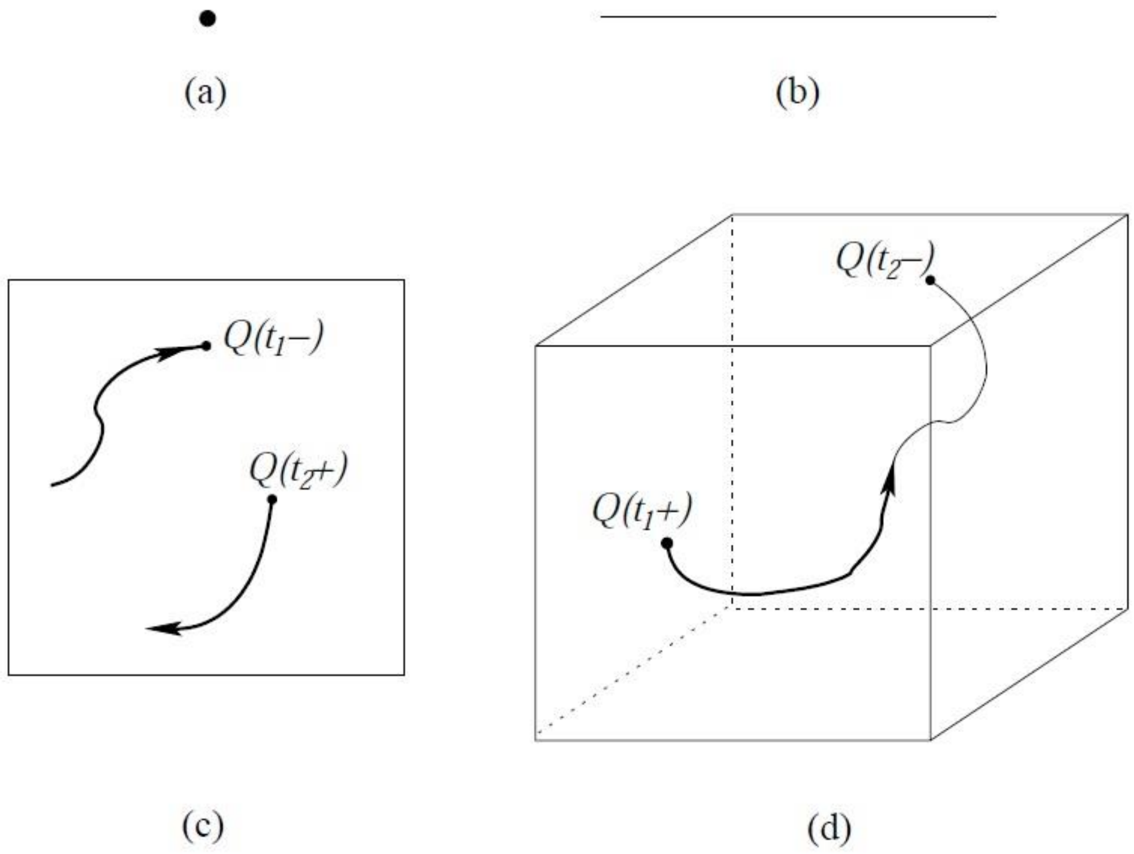
NB: in the usual NRBM we cannot permute particles since they are labelled: if there is a permutation, it will entails a different trajectory for the particle;

Ontology



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Here, as in NRBM, Ψ_t has a double role: it guides the particles' motion and determines the statistical distribution of the positions.

Ontology

- To sum up:
- Particles have positions at any given time in a real physical space

$$\downarrow$$

Possible configurations of particles have a representation in a position's space $\Gamma\mathcal{Q}^{[n]}$;

- Ψ_t is a vector in an appropriate Fock space;

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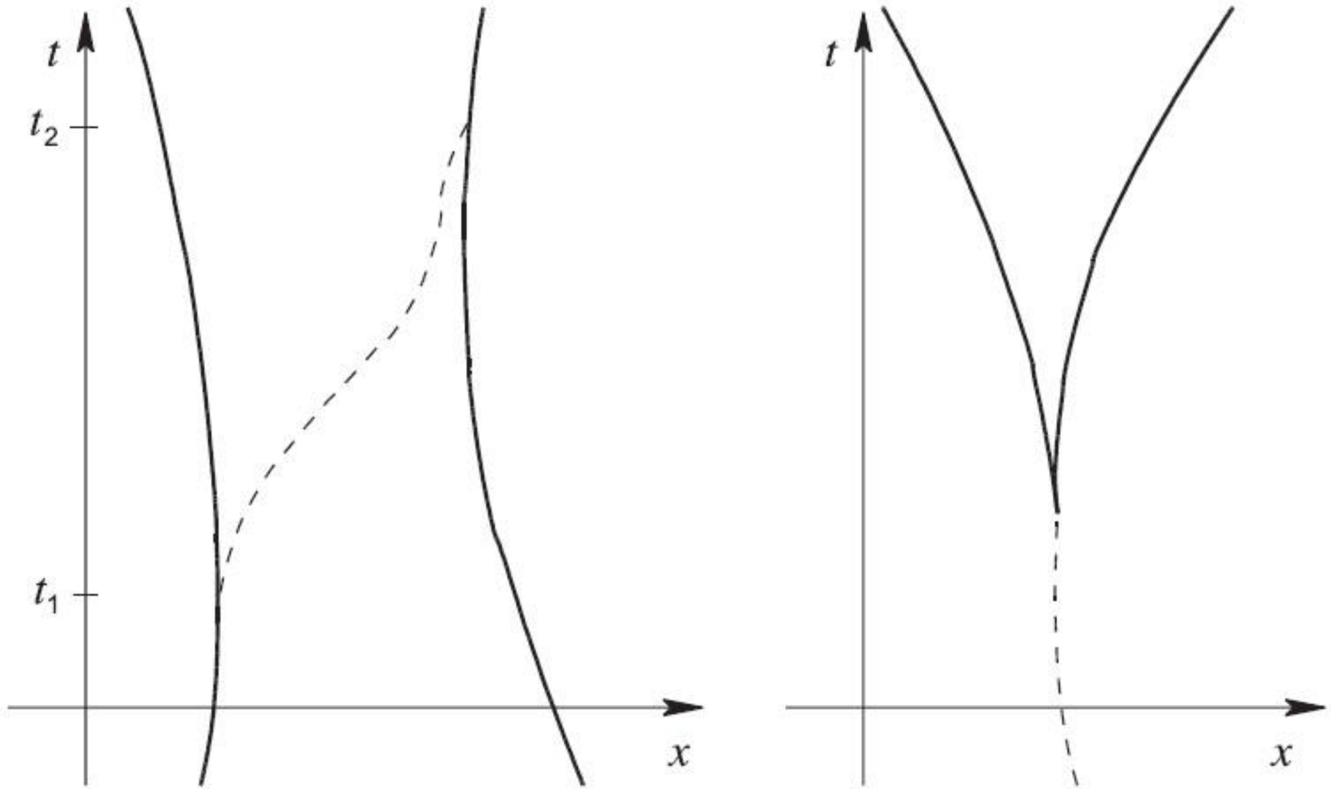
  it corresponds to a creation/annihilation event
- These events are the novel element respect standard bohmian trajectories, but trivially they are essential to explain processes involving particle creation and annihilation;
- NB: these events are intrinsically stochastic, so the evolution of a physical system in this theory will not be deterministic, in opposition to the non relativistic regime (here we will call these random events "jumps").

Dynamics



(a) (b)

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- Where to jump;
- How to move between the jumps → deterministic evolution;

- The state vector evolves according to the Schrödinger equation;
- NB: generally speaking, world lines follow classical bohmian trajectories interrupted randomly by stochastic jumps which correspond to particle creation/annihilation events.

Dynamics

- What do we mean when we say that a certain configuration follows classical bohmian trajectories?

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- The law of motion for Q_t depends on the state vector and on its Hamiltonian

↓

the "continuous" path of a world line is governed by a first-order differential equation which is very close to the bohmian guidance equation:

$$\frac{dQ_t}{dt} = v^{\Psi_t} = \mathrm{Re}\frac{\overline{\Psi_t}\,(Q_t)(\dot{q}\Psi_t)Q_t}{\overline{\Psi_t}(Q_t)\Psi_t(Q_t)}$$

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It corresponds to a deterministic motion

given by a velocity field in configuration space

It defines the deterministic path of the world lines between the jumps;

Dynamics

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- σ is a transition from a configuration q to a configuration q' at time t;
- H_{tot} appears in the Schrödinger equation for Ψ, thus it becomes clear how the law of motion for the configuration of particles depends on Ψ and H_{tot}.

Dynamics

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- The jump rate, which depends on the configuration, on the state vector and on H_{tot}, is given by

$$\sigma(q', q, t) = \frac{2}{\hbar} \frac{(\mathrm{Im}\overline{\Psi(q)}\langle q|H_{int}|q'\rangle\Psi(q'))^{+}}{\overline{\Psi(q)}\Psi(q)}$$

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To sum up, the total Hamiltonian gives a "deterministic" motion with velocity v randomly interrupted by jumps with rate σ after each of which the deterministic motion is resumed (and again interrupted).

Dynamics

- The possible jumps are very restricted and they can change the particles' number only by ± 1

1) appearance of a particle (e.g. emission)
2) disappearance of a particle (e.g. absorption)
3) replacement of one particle by two particles (creation)
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- What is stochastic about Q_t?

a) The times at which jumps occur;
b) The destination of the jumps;

Equivariance

- The probabilities for a) and b) are governed by the wave function

$\downarrow$

If $Q(t_0)$ is chosen at random with distribution $|\Psi(t_0)|^2$, then at every later time $t > t_0$ $Q(t)$is distributed with density $|\Psi(t)|^2$

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- This process is *equivariant*, and it establishes the *empirical equivalence* between BQFT and standard QFT;
- NB: equivariance in BQFT is differently understood respect NRBM in virtue of the stochastic nature of the events which are observed at the QFT level.

Equivariance

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- Here Markov processes are candidates for the equivariant motion of the configuration;
- Markovian processes involve transition probabilities from one configuration to another $\rightarrow$ this is completely adherent to the stochasticity of jumps rates for creation/annihilation events;
- These probabilities are characterized by a linear operator called forward generator L_t
- The distribution ρ_t of Q_t evolves according to

$$\frac{\partial \rho_t}{\partial t} = L_t \rho_t.$$

Equivariance

- Generalization of equivariance from deterministic to Markovian processes:

given the transition probabilities, the $|\Psi|^2$- distribution is equivariant iff for all times $t$and t' with $t' > t$ the distribution Q_t with distribution $|\Psi|^2$ evolves into a configuration $Q_{t'}$ with distribution $|\Psi_{t'}|^2$.

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- To close the circle: "A jump process is a Markov process on configuration space for which the only motion that occurs is via jumps".

Malament's theorem

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- Main claim: there cannot be a relativistic quantum theory of localizable particles;
- All talk about particles has to be understood as talk about fields → particles are defined as field's excitations → fields are the beables of the theory;
- Malament's aim: to show the physical impossibility to have a quantum filed theory with a particle ontology;
- The notion of "particle" entails some peculiar features among which its localizability: this result is concerned with this property

↓

The theorem is about position measurement of a (supposed) localized particle in Minkowski spacetime and shows how we cannot localize a particle in this space, no matter where we perform the measurement;

NB: in SQM particles are not localized but localizable

Malament's theorem

- The arena: Minkowski spacetime;
- Let $\mathcal{M}$ be a Minkowski spacetime, and let S be a family of parallel spacelike hyperplanes that cover $\mathcal{M}$;
- Let us take a spatial set Δ to be any bounded open set within some particular S_i;
- NB: for the following argument it is no important how large is Δ;

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- NB: for the following argument it is no important how large is Δ;
- Definition of a quantum state:

1) $\mathcal{H}$ Hilbert space, the rays of which represent the pure state of our system;
2) An assignment to each spatial set Δ of a projection operator P_Δ on $\mathcal{H}$;
3) A unitary $\mathbf{a} \mapsto U(\mathbf{a})$ representation in $\mathcal{H}$ of the translation group in $\mathcal{M}$;

Malament's theorem

- Here P_Δ means the event that the particle would be found in Δ if a particular detection experiment were performed;
- Conditions on the structure $(\mathcal{H}, \Delta \mapsto P_\Delta, \mathbf{a} \mapsto U(\mathbf{a}))$

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where $P_{\Delta+\mathbf{a}}$ is a result one obtains translating Δ by $\mathbf{a}$;

This condition means that the statistics of a measurement does not change with spatial translations: We can suppose to conduct the experiment not at its original site, but translated in another place, which is displaced from the first by $\mathbf{a}$: $P_{\Delta+\mathbf{a}}$ represents the event that if a particular experiment were performed, the particle would be found in $\Delta + \mathbf{a}$.

Malament's theorem

2) Energy Condition:

For all future directed timelike vectors $\mathbf{a}$ in $\mathcal{M}$, if $H(\mathbf{a})$ is the unique self-adjoint hamiltonian operator satisfying

$$U(t, \mathbf{a}) = e^{-iH(\mathbf{a})}$$

then the spectrum of $H(\mathbf{a})$ is bounded below;

This condition says that a particle has a ground energy state;

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3) Localizability Condition:

If Δ_1, Δ_2 are disjoint spatial sets of a single S, then

$$P_{\Delta_1}P_{\Delta_2} = P_{\Delta_2}P_{\Delta_1} = 0$$

this condition rules out the “infinite speed” possibility for a particle: a particle cannot be detected in two disjoints (spacelike related) spatial sets at the same given time;

Malament's theorem

4) Locality Condition:

If Δ_1, Δ_2 are spatial sets (not necessarily on the same hyperplane) that are spacelike related, then

$$P_{\Delta_1} P_{\Delta_2} = P_{\Delta_2} P_{\Delta_1}$$

Here it is imposed the "stamp of relativity", the independence of outcomes holds in time → the statistical independence of position measurements is propagated and preserved in time!

Malament's theorem

- Claim: Malament's theorem

If the structure $(\mathcal{H}, \Delta \mapsto P_\Delta, \mathbf{a} \mapsto U(\boldsymbol{a}))$ satisfies condition (1)-(4), then

$$P_\Delta = 0, in\ every\ \Delta$$

- Conclusion: any candidate of a particle relativistic quantum theory that satisfies these conditions must predict that the probability to find the particle in any Δ is 0. Since this conclusion is not acceptable, the claim assumes the status of a no-go theorem for a particle ontology.

Discussion

- Two options on the table:

1) Malament's theorem shows how it is physically impossible to have a consistent theory with a particles ontology;
2) Bohmian QFT, a quantum field theory of particles which is empirically adequate since it recovers all the set of predictions of standard QFT;

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2) Bohmian QFT, a quantum field theory of particles which is empirically adequate since it recovers all the set of predictions of standard QFT;

- Questions:
- Could we apply Malament's result to the structure of Bohmian QFT?
- If it were not the case, which kind of arguments do we have to dismiss this theorem?

Discussion

- Malament's theorem is based on the usual SQM formalism: the description of a physical system is provided only in terms of the wave function;
- The theorem is concerned with measurements of position operator, it is not about particles

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here is valid the same argument against SQM

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BM and BQFT have a richer and clearer ontological structure: we assume that our world is *made of* particles, our primitive variables, which have definite positions at any given time;

- The "primitiveness" of PO ⇒ two different aspects:

a) primitive variables are "irreducible" to others notions, they are not inferred o derived from other entities;

b) explanatory function of the primitive variables: they are primitive because every physical object or phenomenon must be connected and explained in terms of PO;

Discussion

- Realism about operators, two quotations:
- The concept of 'measurement' becomes so fuzzy on reflection that it is quite surprising to have it appearing in physical theory *at the most fundamental level*. […] Does not any *analysis* of measurement require concepts more *fundamental* than measurement? And should not the fundamental theory be about these more fundamental concepts? (Bell, 1981)

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- Here are some words which, however legitimate and necessary in application, have no place in a *formulation* with any pretension to physical precision: *system; apparatus; environment; microscopic, macroscopic; reversible, irreversible; observable; information; measurement*. […] The notions of "microscopic" and "macroscopic" defy precise definition. […] Einstein said that it is theory which decides what is "observable". I think he was right. […]"observation" is a complicated and theory-laden business. Then that notion should not appear in the *formulation* of fundamental theory. (Bell, 1990)

Discussion

- Malament's argument excludes non local interactions, while BQFT incorporate non locality in its dynamical equation for the primitive variables

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as in the non relativistic regime, the velocity of particles depends on the entire configuration

- The point here is that within the bohmian framework one is not trying to "make the standard QFT a bohmian one", rather one is trying to built up a new physical theory with different features respect standard QFT;

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- The point here is that within the bohmian framework one is not trying to "make the standard QFT a bohmian one", rather one is trying to built up a new physical theory with different features respect standard QFT;
- In conclusion we have a different structure for the definition and the description of a quantum system than $(\mathcal{H}, \Delta \mapsto P_\Delta, \mathbf{a} \mapsto U(\boldsymbol{a}))$

$$\downarrow$$

a description which includes physical assumptions about the primitive ontology;

Conclusions

- BQFT is a counterexample to Malament's theorem, so it is possible to have a theory with a particle ontology;
- BQFT is however an *effective* theory: we have to introduce cut offs (UV and IR) in order to have well defined Hamiltonians;

Conclusions

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- BQFT is however an *effective* theory: we have to introduce cut offs (UV and IR) in order to have well defined Hamiltonians;
- Here effective means only that this theory is not strictly speaking a fundamental theory → e.g. gravitational phenomena are not explained (this is also the case of any QFT)

↓

Effectiveness has not to be regarded as a negative feature: it says only that a certain theory has limits in its applications: we cannot say anything under certain physical energies!

Conclusions

- Lorentz invariance: BQFT requires a preferred reference frame, therefore it is not Lorentz invariant

- However, the theory is empirically equivalent to a Lorentz-invariant theory

↓

Experimentally there are no possibilities for an observer to determine which frame is the preferred one, so the BQFT's empirical predictions are Lorentz invariant

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BQFT is equivalent to a fully Lorentz-invariant theory.

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- Figure 1 and figure 2 (R. Tumulka) have been taken from DGTZ 2004.