IPP-QM-6: Bohmian mechanics

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MT24

The course

1. Basic quantum formalism
2. Density operators and entanglement
3. Decoherence
4. The measurement problem
5. Dynamical collapse theories
6. Bohmian mechanics
7. Everettian structure
8. Everettian probability
9. EPR and Bell's theorem
10. The Bell-CHSH inequalities and possible responses
11. Contextuality
12. The PBR theorem
13. Quantum logic
14. Pragmatism and QBism
15. Relational quantum mechanics
16. Wavefunction realism

Today

Hidden variable theories

Bohmian mechanics introduced

Bohmian mechanics meets some important experiments

Contextuality and non-locality

Objections to Bohmian mechanics

Alternative approaches to Bohmian mechanics

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- Recall that we can’t *simultaneously* know the physical properties of a system corresponding to non-commuting observables (e.g. spin with respect to the x- and z-axes at the same time; or position and momentum of some particle at the same time).
- Hidden variable theorists insist that the quantum mechanical systems of interest *really do* have determinate properties at all times—so our inability to simultaneously *determine* properties of systems such as those mentioned above is an *epistemic*, rather than *ontic*, deficiency.

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But these claims are wrong, as we'll see!

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The hidden variable theory known as *Bohmian mechanics* manages to evade all three of these!

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- ...indeed, as we'll see, position is the *only* property that these particles have.

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- Promoted by Goldstein, Dürr, Zanghí, *et al.*, 1990s onwards, as “Bohmian mechanics”.

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1. *The wavefunction*: The eponymous 'pilot wave' $\psi(x_1, \ldots, x_N)$ (where N is the number of particles).
2. *The corpuscles*: Point particles with determinate positions $q_1, \ldots, q_N$.

Intermezzo: local beables and primitive ontology

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- (For more on the notion of primitive ontology, see (Allori *et al*. 2008) and (Allori 2015).)

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- Probabilistic hypothesis: At some arbitrary time t, the probability distribution of the corpuscle positions is given by

$$\Pr\left(q_1 = x_1,\ldots,q_N = x_N\right) = \left|\psi\right|^2\left(x_1,\ldots,x_N\right).$$

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- In other words, these probabilities in Bohmian mechanics must always be understood as *epistemic*, rather than *ontic*.

Relaxing the quantum equilibrium hypothesis

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- One corollary of these dynamical strategies is that the universe—or at least, some subsystems of it—might not be in 'quantum equilibrium' after all.
- This would create *observable* violations of the predictions of quantum mechanics, and might provide a context in which hidden variable theories could be tested.

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- The guidance equation then ensures that the quantum mechanical probabilities are *always* given by the Born rule.
- Bohmian mechanics purports to solve the measurement problem as, given any state of the wavefunction that seems to involve macroscopic superpositions, the corpuscle picks out one branch as real. (We will see this in more detail very soon.)

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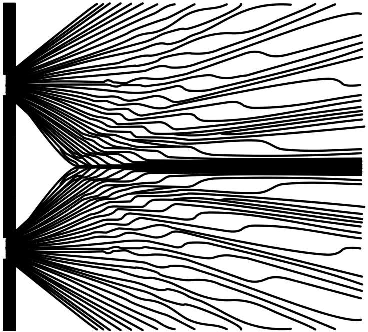

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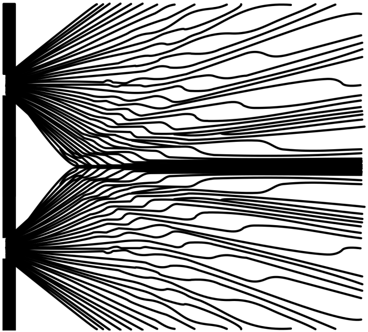

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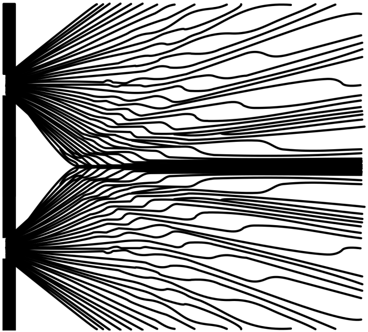

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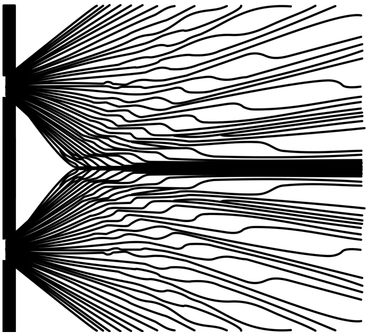

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- The wavefunction 'guides' the particle, leading to the uneven, interference-*like* distribution on the screen.

Stern-Gerlach experiments

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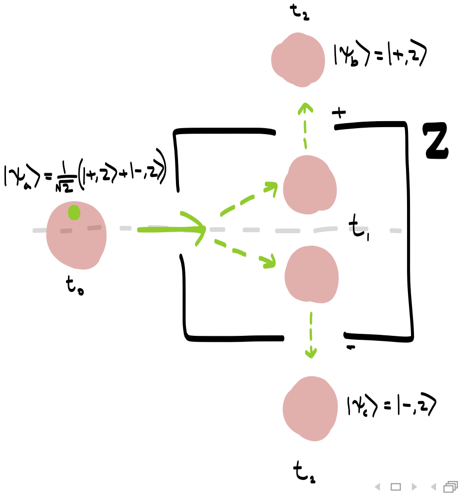

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- In Bohmian mechanics, all future positions of the electron can in principle be determined from its present position, and so the aperture through which it will ultimately exit can be determined from its initial position.

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- In this spin experiment, the *contextuality* of Bohmian mechanics can be illustrated straightforwardly: just reorient the appratus so the ‘spin down’ slot is at the top.
- Even though Bohmian mechanics is a deterministic theory, the outcome of this sort of ‘measurement’ will in general not be pinned down in the theory—but will rather depend upon precisely how and under what circumstances the observable in question gets measured. (As it should, given the BKS theorem.)

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- Therefore, properties such as spin, are not intrinsic to the Bohm corpuscles.
- The only *intrinsic* property the particle possesses is position.

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The non-locality of Bohmian mechanics really is manifest in the guidance equation:

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In particular, we'll look at the following four objections:

1. Worries about the dynamics
2. Worries about the ontology
3. 'Everett in denial'?
4. Compatibility with relativity

Objection 1: The dynamics

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(B) The *action-reaction principle* is violated: the wavefunction acts on the corpuscles, but is not affected by them.

- *Responses*: Why buy into the action-reaction principle?
- *And:* This might be seen as a reason not to take the wavefunction to represent real physical structure, in which case the Bohmian can (try to) avoid the problem. (More on this later.)

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  - In these experiments, a magnetic field is found to alter the trajectory of a particle which is never located where the field is located.

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- To bring this out further, consider the case of neutron interferometry discussed by Brown *et al.* (1995)
  - In these experiments, a magnetic field is found to alter the trajectory of a particle which is never located where the field is located.
  - If this is the case, Brown *et al.* infer that the relevant properties of the particle (such as mass and charge) must be properties of the wavefunction, not of the corpuscle.

Objection 2: The ontology

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  - So: maybe everything relevant is in the wavefunction...

Objection 3: Everett in denial?

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Reponse: This depends upon (a) an interpretation of the wavefunction as representing physical goings-on; and (b) Everettians' particular functionalist ontology—more on which in Lecture 7.

Objection 4: Lorentz invariance

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- Nor can it easily be modified to accommodate Lorentz invariance.
- Configurations, defined by the *simultaneous* positions of all particles, play too crucial a role in its formulation, with the guidance equation defining an evolution on *configuration* space.

Emergent Lorentz symmetries

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- In this view Lorentz invariance in such a theory would be an emergent symmetry obeyed by our observations.

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- For this reason, Wallace (2022) maintains that there isn't even a *bona fide* case of underdetermination between Bohmian mechanics and Everett—for no QFT-appropriate version of Bohmian mechanics currently exists.
- (Recall that we saw this objection made also to dynamical collapse theories in the previous lecture.)
- Bohmians see this as less of a problem and more of an ongoing research programme... (**Question:** Is this a satisfying response?)

Today

Hidden variable theories

Bohmian mechanics introduced

Bohmian mechanics meets some important experiments

Contextuality and non-locality

Objections to Bohmian mechanics

Alternative approaches to Bohmian mechanics

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Naturally, the Bohmian apparently having to view the wavefunction as real ties in with e.g. the 'Everett in denial' objection.

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- But this (one might claim) is problematic! The wavefunction itself is guided by the time-dependent Schrödinger equation, and (one might claim) laws shouldn't themselves be governed by other laws!
- Dürr, Goldstein, and Zanghì claim that we should see the time-dependent Schrödinger equation as purely phenomenological: it arises locally, but the real solution to the wavefunction of the whole universe is just a stationary state.

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- (Note that Huggett’s ‘regularity relationalism’, discussed in the SR part of the IPP course, is another version of super-Humeanism.)
- **Question:** Is this just a promissory note?

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Next week: *the Everett interpretation*.

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