Conceptual Issues In Quantum Mechanics

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Quantum Mechanics

- Quantum Mechanics (QM) is a description of matter and its dynamics at the microsopic regime;
- Therefore, *QM is about* molecules, atoms, electrons, nucleons and so on; The theory describes these entities, their temporal evolution and their properties with the following axioms.

Axioms

1. States: In QM physical states are described by state vectors on Hilbert space (the space of states)

- Equivalently, they are described by wave functions in configuration space (position representation)

The state vector (wave function) contains all the information regarding physical systems; thus, one could compute any parameter of the system from it.

Axioms

2. Dynamics: The evolution of a (closed) system is unitary.

- The state vector at time t_n is derived from the state vector at time t_0. Application of the Unitary Operator $U(t, t_0)$.

- This is equivalent to say that the temporal evolution for state vectors and wave functions is given by the Schrödinger Equation.

Axioms

3. Observables: Every physical property A is associated with an operator O in Hilbert space which acts on the system.

- Eigenvalues: the possible values of the physical property; the set of all possible eigenvalues of O is the spectrum of O;

- Eigenstates: possible physical states in which the system could be (related with eigenvalues);

Axioms

4. Born Rule: if $|\psi\rangle$ represents a physical state of a system and $|\varphi\rangle$ represents another physical state, then the probability to find $|\psi\rangle$ in the state $|\varphi\rangle$ is given by the squared modulus of their scalar product: $p(|\psi\rangle,|\varphi\rangle) = |\langle\psi|\varphi\rangle|^2$

- If we consider a wave function of a particle, the Born rule states that the probability density *p(x,y,z)* for a position measurement at time *t* is given by

$$p(x,y,z) = |\psi(x,y,z,t)|^2$$

- In the second formulation of the Born rule it is clearer the dependence on measurements.

Axioms

5. Collapse: *if* a system interacts with an experimental device, the Schrödinger evolution is suppressed.

- The system is projected into one of the possible eigenstates corresponding to the effective outcome of the measurement.
- The collapse of the wave function is completely stochastic.

Measurement

- Measurement: interaction between physical systems (quantum) and experimental devices (classical);
- In QM the latter ones are not considered in the equations;
- Is there an intrinsic limitation in the domain of application of QM?
- Is there an arbitrary (non defined) division between quantum and classical regime?

Measurement

- Observables are identified with Operators
- What kind of information do we obtain from an operator?
- What does it mean exactly «to measure an operator»?

Measurement

- Measurement entails the notion of observer;
- Do we have a rigorous definition of «observer»?
- Do we need such a definiton?

Measurement

- Temporal Evolution: Schrödinger equation (linear and deterministic) + collapse postulate (stochastic);
- Do we have an inconsistency between these to dynamical laws?
- When is the Schrödinger dynamics valid?
- Measurement Problem (Schrödinger 1935);

Measurement

- It seems that axioms and physical laws concerns our epistemic access to the quantum world instead of a realistic description of quantum phenomena.
- QM as *phenomenological* algorhytm; a set of rules for computing the probability of measurements' outcomes

Measurement

- J. S Bell, Against Measurement (from DGZ 2004):

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. Less surprising perhaps is that mathematicians, who need only simple axioms about otherwise undefined objects, have been able to write extensive works on quantum measurement theory—which experimental physicists do not find it necessary to read. . . . Does not any analysis of measurement require concepts more fundamental than measurement?And should not the fundamental theory be about these more fundamental concepts?

Measurement

- Again Bell:
- 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.

Completeness

- Einstein Boxes: Either we accept incompleteness of the wave function (= we reject Axiom 1) or locality must be violated;
- Einstein (1927) and Schrödinger (1935) are the main objections against this formulation of QM in the first half of the previous century; they raised *different* problematic points of the theory.

Complementarity

- Leaving aside issues about the completeness of the wave function, consider the following question:
- What kind of description do we have of quantum objects?
- Complementarity;
- Complemetarity depends on Measurements;
- QM: *Local Beables are Local Observables*

CM and QM

- CM has the following properties:
- Determinism;
- Continuous temporal evolution;
- Effective properties of systems;
- Separability;
- Observer Independence;

❑ What about QM?

Conclusion

- What do we need?
- *Ontological Clarity*: a theory should claim clearly its fundamental entities, which are supposed to be the basic objects form which we could recover our manifest image of the world;
- *Observers Independence*: the notion of "observer" is rather vague and should not play any crucial role in a fundamental physical theory;
- *Non-vagueness*: it should be clear the domain in which the theory is valid;

References

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