QUANTUM MECHANICS AND PARADIGM SHIFTS

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Main Thesis: classical and quantum mechanics are not necessarily as radically different as they have been depicted so far: I will show that it is possible to construct quantum theories completely compatible with the "old" classical paradigm.

- Classical Mechanics (CM) is not a very controversial theory:
  - Clear metaphysics (particles) which grounds a scheme of explanation that arguably allows determining the properties of macroscopic physical objects in terms of the behavior of the fundamental objects in the theory employing standard methodologies.
- Too bad it seems we have to abandon such clear scheme once we consider quantum mechanics: <u>We HAVE TO change our paradigm</u>! … Do we? **<u>NO…</u>**
- How did it happen that people get convinced of these things?

History of the development of quantum mechanics:

- End of the 19th century: Newtonian picture of the world as made of particles;
- Beginning of 20th century: some experiments were taken to show that particles sometimes behave like waves.
- But particles and waves are <u>incompatible ontologies</u>! So, it appears that we need to revise our ways of understanding and describing reality:
  - Particles and waves are obsolete concepts, inadequate to represent the quantum reality, and should therefore be abandoned. In addition, since in the quantum world superpositions are possible, the laws of classical logic such as bivalence do not hold any longer (quantum logic)
- <u>An attempt to save the classical paradigm</u>, Louis de Broglie's wave function: Let us associate such <u>wave</u> to each <u>particle</u> as a "guide field" whose evolution was later described by Erwin Schrödinger.

  - De Brogie's idea was quickly abandoned: due to heavy criticism by Wolfgang Pauli at the 1928 Solvay Congress, and to other results (such as Heisenberg's uncertainty principle, and von Neumann 's theorem) which were taken to show that quantum theories had to be <u>about the wave function</u>, and not about particles.

But even if we attempt to interpret quantum mechanics realistically as a theory about the <u>wave function</u> we fail → **Schrödinger's measurement problem:** if the wave function completely describes physical systems, and it evolves according to the Schrödinger equation, then macroscopic superpositions which we clearly never observe are produced.

Proposed solution of the measurement problem:

The early years:

- <u>Wigner:</u> the wave function is collapsed in one of the terms of the superpositions by an observer;
- <u>Von Neumann:</u> there are two distinct and fundamentally irreducible worlds, the classical and the quantum one.
- Neither of these two approaches is close to the previously accepted paradigm of CM. So it seems we have <u>a paradigm shift</u>: either in one world-view consciousness actively participates to physics, or ordinary concepts and the laws of classical logic are not valid any longer.

Eventually, new and <u>less problematic proposals</u> to solve the measurement problems were made.

- <u>David Bohm</u> (1952): He revised and updated deBrogie's particle-wave theory and showed that his theory solves the measurement problem.
  - Theory dismissed for a very long time (on the basis of a mistaken interpretation of von Neumann's theorem), and only fairly recently appreciated (Bohmian Mechanics, BM)
- <u>Hugh Everett</u> (1957): He developed the so called many-worlds interpretation, in which the terms of the superpositions are interpreted as belonging to different worlds to which we have no access, so that everything that can happen (all superpositions) will happen, but in a different world (Many -Worlds).
- <u>Ghirardi, Rimini and Weber</u> (1986): They developed a theory in which the wave function does not evolve according to Schrödinger's equation but it randomly collapses in one of the terms of the superpositions not because of an observer but as a result of a physical law (GRW).

Quantum Theories with Paradigm Shift: The three examples presented above show how it is possible to provide realist interpretations of the quantum formalism that do not rely on the notion of the observer. They are "quantum theories without observers" (QTWO)

- All these theories were naturally taken to be <u>theories about the wave function</u>:

    - If in a physical theory there is a fundamental equation for the evolution of a given mathematical object, generally we think we are justified to take this object to represent physical objects.
    - In CM, the fundamental equation is Newton's equation, and it describes the temporal evolution of point-particles n three--dimensional space. We therefore conclude that CM describes the behavior of point--like particles.
    - By analogy, in QM the fundamental equation is Schrödinger's equation, and given it is an equation for the temporal evolution of the wave function, we are entitled to take the wave function to represent physical objects as well.
- Problems for the view:
    - Physical space is not the traditional three--dimensional space, but it is the space on which the wave function is defined, namely configuration space. Clearly, we do not seem to live in configuration space: rather, it seems obvious to us that we live in three--dimensions. Therefore, a proponent of such a view has to provide an account of why it seems as if we live in a three--dimensional space even though we do not. Also, she should explain how to "recover the appearances" of macroscopic objects in terms of the wave function.
- If this reading of QM is correct, we nonetheless have a paradigm shift: we move from the classical, commonsensical view that there are microscopic objects in regular three-dimensional space (particles and fields) that compose macroscopic familiar objects, to the quantum view in which we all live together in configuration space, and we cannot use any longer the rules of compositionality and reduction as we could do within the classical paradigm.

Quantum Theories with no Paradigm Shift: The paradigm shift arises from taking the wave function as describing physical objects. I will argue here that it is not necessary to go along this route, so that we can avoid the paradigm shift. With a QTWO which is not about the wave function, but about microscopic *stuff in* space—time, we can develop a clear explanatory scheme, on the line of the classical one, to account for the macroscopic world. As a consequence, there is no quantum revolution as advertised so far: the quantum world is less crazy and paradoxical than one would have thought.

- How is this done? Let us go back to BM:
    - One could think of it as a theory about both particles and the wave function: in BM we have two fundamental equations, one for the wave function and one for the particles, and they describe what there is.
    - But if we look closely to the structure of the theory we will see that this approach is contrived: in BM the wave function has a particular role of describing the way in which matter moves, not matter itself.
    - So, it seems more appropriate to think of it as representing a law or perhaps a property, rather than physical objects themselves.
- With this understanding of the role of the wave function in BM, look to the other QTWO:
    - GRW:
        - GRWm: matter is described by a field in three--dimensional space defined in terms of the wave function,
        - GRWf: matter exists in space—time called "flashes," whose rate depends on the wave function.
            - In both GRWm and GRWf the evolution of matter is determined by the wave function, which in turns evolves according to the modified GRW dynamics.
    - Many-world:
        - Sm: a matter density field ontology in three-dimensional space, as in GRWm, combined with a Schrödinger evolving wave function which determines the temporal evolution of the primitive variables.

In this framework, there is no paradigm shift at all. **QM has the same structure as CM**: there is microscopic stuff in ordinary physical space that moves in time and this microscopic *stuff* combines together to form the familiar macroscopic objects of our experience. Because of this, also in QM we should be able to recover, at least in principle, all the macroscopic properties of physical objects using an explanatory scheme derived along the lines of the classical one.

Conclusion: No paradigm shift is needed to account for the quantum world. If we like to drastically change our way of understanding the world through physics we can, but we do not have to.