Quantum State: Information, Free Choice, Randomness

Quantum mechanics provides exceptionally accurate predictions of measurement results, yet, the answer what the world must be like for quantum mechanics to be true, has proved to be exceedingly elusive. Reflecting on some recent developments, our project aims nevertheless to contribute to the understanding of quantum reality, the common thread of our investigation being the concept of quantum state. We will be investigating three themes important in this topic: the epistemic view on quantum states, the condition of Settings Independence, and the issue of indeterminism of quantum mechanics.

The predictions of measurement outcomes in quantum mechanics are obtained in the following way. First, we ascribe to the system an appropriate quantum state (on the basis of how it has been prepared). Next, we calculate the evolution of this state in accordance with the Schrödinger equation. Finally, we perform the measurement; the probabilities of its outcomes are read off from the quantum state at the moment of measurement by means of the Born rule. Importantly, the Born rule does not specify the exact outcomes of experiments, but only the probabilities of possible outcomes. This duality of evolution rules (the Schrödinger equation and the Born rule) leads to the measurement problem, which is the major obstacle in the attempts to understand quantum mechanics.

As is visible in the above description, the quantum state is the central object of quantum mechanics. In the light of difficulties inherent to the attempts to understand this object as representing something physically real (i.e., the ontic interpretation), an idea have arisen that perhaps it should be interpreted epistemically – that is, as representing agents' beliefs. Our first aim is the critical analysis of contemporary variants of this view. Among them, the most important are the following three: (i) QBism, (ii) the discussion within the framework of ontological models, initiated by Harrigan and Spekkens (*Found. of Phys.* 40, 2010), and (iii) the construction of epistemic models resembling quantum mechanics, initiated by Spekkens (*Phys. Rev. A* 75, 2007)). The novelty of our research programme is that we want to take into account the conceptual distinctions and tools of contemporary epistemology. In particular, we make a hypothesis that the mentioned approaches are at certain points conceptually problematic, as they ignore some crucial features of the concept of knowledge (e.g., that knowledge that p entails that "p" is true).

Another attempt to understand the nature of quantum realm begins with the assumption that quantum mechanics is not complete and it should be supplemented by additional variables (the so-called "hidden variables"), which represent those properties of the physical system that are not captured by the quantum state. It turns out that there are significant constraints on theories of this type, as has been shown by a series of theorems, starting with the famous Bell's theorem (*Physics* 1(3), 1964). This theorem excludes the possibility of hidden variable theories that satisfy jointly three conditions: Outcome Independence, Parameter Independence, and Settings Independence. However, one can construct hidden variable theories violating at least one of them. So far the literature has been focused on the first two of these conditions, but recently there emerged attempts to consider theories violating the third condition (e.g., Ciepielewski et al., *Brit. Journ. Phil.* 2022). This is controversial because Settings Independence seems to be related to the freedom of the choice of experiment's settings by an agent. Our aim is to consider the consequences of violating this condition and the formal analysis of the condition itself, taking into account its model nature (i.e., its being related to the concepts of possibility and necessity). The latter task will be conducted using the framework of Branching Space-Times (see Belnap, Müller and Placek, *Branching Space-Times: Theory and Applications*, Oxford University Press 2022), which is appropriate for this purpose, as it allows one to analyse modal notions in the relativistic context.

Our third subject of investigation will be the question whether quantum mechanics is indeterministic. Here, our primary goal will be to review and assess various possible analyses of determinism and indeterminism, since it turns out that these notions can be defined in different and non-equivalent ways. We plan to consider at least six different approaches: (1) syntactic (i.e., based on the linguistic structure of a theory, neglected after the criticism by Montague (*Formal Philosophy*, Yale University Press 1974), in our opinion too quickly), (2) semantic (i.e., based on the qualitative identity of the models of a theory), (3) branching-style, based on primitive modality, (4) invoking the intuition of "producing" new states of the world from the earlier states, (5) based on the uniqueness of solutions of differential equations, (6) a new approach by Landsman (2020, arXiv:2003.03554) that uses the notion of randomness as it is understood in mathematical computability theory. According to Landsman, quantum mechanics is indeterministic because the series of outcomes of experiments given by the Born rule are random in the mentioned sense. However, he does not provide any particular definition of indeterminism, leaving this as an open research question; he only assumes that randomness is sufficient for indeterminism. We want to tackle precisely this question, and also discuss whether associating the notion of indeterminism with randomness is defensible (which is sometimes questioned, see e.g. Eagle 2021, https://plato.stanford.edu/archives/spr2021/entries/chance-randomness). Additionally, we would like to investigate what is the source of randomness in the case of the Born rule and whether other variants of quantum mechanics that do not use it also generate randomness.