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EDITORIAL

Preface of the Special Issue Probing the Limits of Quantum Mechanics: Theory and Experiment, Volume 2

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This volume is the second of the two volumes presenting theoretical and experimental viewpoints on foundational problems of quantum physics that are directly related to quantum information and technology. Contributions are clustered in the following three sections:

- General problems of quantum foundations
- Philosophical significance of quantum reconstruction theorems
- Quantum-like models: from molecular biology to cognitive psychology and economics

1 General Problems of Quantum Foundations

This section contains contributions, by both theoreticians and experimentalists, to quantum foundations, along with contributions devoted to related mathematical problems. Here we highlight some of these contributions. On the experimental side, we would like to mention the article by Curceanu et al. "Spontaneously emitted X-rays: an experimental signature of the dynamical reduction models", which presents the novel idea of searching for X-rays as a signature of the mechanism inducing the spontaneous collapse of the wave function. This type of signal is predicted by the continuous

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spontaneous localization theories, which aim to solve the "measurement problem" by modifying the Schrödinger equation to accommodate the spontaneous collapse. Finding or, conversely, failing to find this signal will help to either establish the viability of such a theory or make it less likely to be correct. Stochastic electrodynamics (SED) is among the more successful attempts to interpret quantum electrodynamics on classical lines, although the approach is not without problems. In quantum theory, the leading non-relativistic corrections to the ground state energy dominate the Lamb shift related to the photon cloud that should cause the quantum-like behavior of SED. Nieuwenhuizen and Liska's article "Simulation of the hydrogen ground state in SEDs-2: Inclusion of relativistic corrections" takes these corrections into account in a numerical modeling of this process. The article shows that they have little effect: the self-ionisation that occurs without them remains present. The relationships and mutual influences (in both directions) between physics and mathematics play a major role in foundational studies in quantum theory. Rosinger, in his provocative article "Five departures in logic, mathematics, and thus—either we like it, or not—in physics as well...", emphasizes that while physics depends on physical intuition, much of this intuition is formulated in terms of mathematics. Mathematics, however, depends on logic. The paper presents three recent new "departures" (from the previous state of affairs) in logic, which have major consequences for mathematics, and two possible and equally significant "departures" in mathematics itself. These five "departures", the article argues, have major implications for physics, some of which, specifically in quantum mechanics and relativity, are considered in the article. Plotnitsky and Khrennikov's article "Reality without realism: On the ontological and epistemological architecture of quantum mechanics" offers a new perspective, defined by its title concept of reality without realism, on the nature of quantum reality and the concept of realism (our ability to represent this reality) in quantum theory, in conjunction with the roles of locality, causality, and probability and statistics there. The article also presents two interpretations of quantum mechanics developed by the authors. Although different insofar as the first interpretation, by Plotnitsky, is nonrealist, and the second, by Khrennikov, is realist, both of these interpretations are statistical, and one of the aims of the article is to explore the statistical rather than merely probabilistic, such as Bayesian, view of quantum mechanics. This section also contains several articles that discuss physical and mathematical problems arising in quantum information theory. Thus, Watanabe's review "On entropy of quantum compound systems" considers the S-mixing entropy and the quantum mutual entropy for general quantum systems, introduced by Ohya. The operational-information approach to quantum-mechanical formalism is considered in "Weyl, Dirac, and Maxwell quantum cellular automata" by Bisio, D' Ariano, Perinotti, and Tosini. The article begins by outlining an elementary automaton theory for the Weyl field, and discussing the composite automata for Dirac and Maxwell fields. Then the authors offer an analysis of the dynamics in the momentum space in terms of a dispersive differential equation for narrow band wave-packets, and an account of the position-space in terms of a discrete path-integral approach. Related problematics are discussed, from a general historical and philosophical perspective of fundamental principles of quantum theory, in Plotnitsky's "A matter of principle: The principles of quantum theory, Dirac's equation, and quantum information". In addition, the article considers D' Ariano, Chiribella, and Perinotti's earlier work on the principles of quantum information theory and D' Ariano and Perinotti's derivation of Dirac's equation from these principles alone, in contrast to Dirac's own and most other derivations of the equation by combining the principles of (special) relativity and quantum theory.

2 Philosophical Significance of Quantum Reconstruction Theorems

In his article "Reconstruction and reinvention in quantum theory", Dickson notes that there are a number of interesting ways to reconstruct quantum theory and suggests that a form of instrumentalism makes good sense of this situation. This view runs against the conventional wisdom that dismisses instrumentalism as "cheap". Dickson, by contrast, considers how an instrumentalist might think about the reconstruction theorems, and, by using the distinction between reconstructing quantum theory and "reinventing" quantum theory, he suggests that there is an adequate (not "cheap") instrumentalist approach to the theory and to these theorems.

Grinbaum's article "Quantum theory as a critical regime of language dynamics" defines the observer by a limit on string complexity and information dynamics, which leads to an emergent continuous model in the critical regime. Restricting the observer to a family of binary codes describing bipartite systems, Grinbaum found strong evidence of an upper bound on bipartite correlations equal to 2.82537. This is measurably different from the Tsirelson bound. The Hilbert space formalism emerges from this mathematical investigation as an effective description of a fundamentally discrete theory in the critical regime. Quantum logic, understood as a reconstruction program, had real successes and genuine limitations. Stairs's article "Quantum logic and quantum reconstruction" offers a synopsis of both and suggests a way of seeing quantum logic in a larger, still thriving context.

3 Quantum-Like Models: From Molecular Biology to Cognitive Psychology and Economics

In recent years, the mathematical formalism of quantum information theory and the use of quantum probability found numerous applications outside physics-in cognitive and social sciences, psychology, decision making, economics, psychology, finances, and politics. In these applications, quantum theory is treated operationally as a mathematical machinery dealing with the contextual probabilistic behavior of systems considered in these fields. There is a large amount of statistical data collected in these domains that do not obey the rules of classical probability theory (Kolmogorov 1933) but that can be successfully treated and modeled in the framework of quantum theory. This approach, thus, uses quantum formalism for treating systems that need not be described by quantum physics, but only need to exhibit nonclassical information-probabilistic features in their behavior.

Several papers in this special issue provide instructive examples of such quantum-like modeling. The paper of Asano et al "Quantum information biology: from information interpretation of quantum mechanics to applications in molecular biology and cognitive psychology", is a characteristic example of quantum-information modeling in biology (broadly considered, so as to include cognitive science and psychology), based on the quantum-like representation of the adaptive dynamics of biological systems. Quantum adaptive dynamics describes, in the most general setting, the mutual adaptivity of information states of systems of any origin (physical, biological, social, political) as well as the mutual adaptivity of their co-observations, including self-observations (such as those performed by the brain). The authors argue that the information interpretation of quantum mechanics (developed, in various forms, by Zeilinger and Brukner, Fuchs and co-authors, D' Ariano and co-authors, and several others) is the most natural interpretation of quantum information biology.

Basieva and Khrennikovs article "On a possibility to combine the order effect with sequential reproducibility for quantum measurements" considers a possible application of the theory of quantum measurement (with atomic and non-atomic instruments) to modeling cognition, specifically by combining the order effect (that plays an essential role in psychology) with the repeatability of the results of measurements (which are represented in the form of "incompatible questions"). The main mathematical result obtained in this paper could be seen as an obstacle for the application of quantum measurement theory that considers atomic instruments and finite-dimensional state spaces to this class of problems. This result could, thus, be interpreted as an indication that it is possible that the quantum measurement theory is not sufficiently general to be applicable to measurements performed in experiments that involve human subjects. However, this problem (which is mathematically nontrivial) has to be studied further by considering non-atomic quantum instruments and infinite-dimensional state spaces.

The article by Haven "Potential functions and the characterization of economics-based information" presents the formulation of quantum mechanics as a diffusion process developed by Nelson. This formulation offers an interesting take on how one can move from classical mechanics to quantum mechanics. In addition to the presence of the real potential function, another type of potential function (customarily denoted as quantum potential) forms an intrinsic part of the theory. The article is an attempt to show how both types of potential functions can have a use in a resolutely macroscopic context like *financial asset pricing.*

We hope that this volume will contribute to foundations of QM and be a step toward a further clarification and demystification of the theory.