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Preface

Guest Editors

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The special issue 'Quantum Foundations & Quantum Information (QF&QI)-13' contains a representative selection of papers given at the 15th Växjö conference on Quantum Foundations, held 10–13 June 2013. This important event in the development of foundational understanding of quantum theory and experiment combined the Marcus Wallenberg symposium 'Quantum Theory: Advances and Problems' (QTAP) and its satellite workshop QF&QI. As previous Växjö conferences, QTAP/ QF&QI was arranged by the International Centre for Mathematical Modeling in Physics, Engineering and Cognitive Sciences, Linnaeus University, Sweden. The organizing committees of QTPA and QF&QI consisted of leading theoreticians and experimentalists, and philosophers with strong interest in quantum foundations:

for QTPA:

- H Atmanspacher (IGPP, Freiburg, Germany/ ETH Zürich, Switzerland).
- A Khrennikov (Linnaeus University, Växjö, Sweden).
- A Migdall (NIST, USA).
- A Plotnitsky (Purdue University, USA).
- S Polyakov (NIST, USA).
- G Weihs (Innsbruck University, Austria).

For QF&QI:

- M D'Ariano (University of Pavia, Italy).
- C Brukner (University of Vienna, Austria).
- E Haven (University of Leicester, UK).
- G Jaeger (Boston University, USA).
- A Khrennikov (Linnaeus University, Sweden).

The following special sessions complemented and strengthened the conference program:

- 'General Questions of Quantum Foundations,' A Khrennikov, organizer.
- 'Probing the limits of quantum mechanics,' G Weihs, organizer.
- 'Complementarity in Quantum Physics and Beyond,' H Atmanspacher and A Plotnitsky, organizers.
- 'Quantum randomness: theory and experiment,' A Migdall and S Polyakov, organizers.
- 'Quantum-classical hybrids,' T Elze, organizer.
- 'Quantum-like models outside physics: from cognition and information retrieval to economics and finances,' P Bruza, J Busemeyer, E Dzhafarov, E Haven and A Khrennikov, organizers.

The Växjö series is the longest continuous series of conferences devoted to quantum foundations in the history of quantum mechanics. As in previous Växjö conferences, we were fortunate to have not only physicists (theorists and experimentalists), but also mathematicians and philosophers discussing the foundations of quantum theory. This was especially beneficial in view of recent developments in quantum information theory. While fundamental questions of

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quantum mechanics, including quantum information theory, quantum computing, cryptography and teleportation have been central topics throughout Växjö conferences, they were given new dimensions during this meeting.

In particular, we would like to emphasize that, nowadays, the problems arising in quantum foundations no longer have only a theoretical significance, but also begin to play an important role in the development of quantum technologies and in justifying the importance they are considered to have. One can mention, as an example, quantum cryptography and the theory of quantum random generators. In these cases, Bell inequality violation is the basic statistical test of 'quantumness' (indeed, this is one of the very few such tests that can be practically implemented, in particular, via the CHSH inequality). Accordingly, both theoretical problems related to Bell-type inequalities, including to the analysis of the corresponding probabilistic structure and the problems related to the implementation of the Bell inequality tests, become very important for technological development. These connections were clearly apparent in the talks given by H De Raedt, A Khrennikov, M Kupczynski, J-Å Larsson, K Michielsen, F Sciarrino, S, Ramelow. Debates concerning the possibility of the performance of a loophole free test for the Bell-type inequalities were as intense as they have always been in Växjö, beginning with the very first Växjö conference in 2000.

The Växjö tradition of presenting new research on quantum axiomatization programs continued with Quantum Bayesianism (QBism) and with the informational axiomatization. For the QBism program C A Fuchs has elucidated the relation of the subjective interpretation of the quantum state in the case of an entangled state and violation of Bell inequality. This special issue contains the paper of C A Fuchs and R Schack devoted to the subjective interpretation of quantum state explaining why it does not represent an element of physical reality. On the other side, the informational program (which has already lead to an axiomatization of quantum theory), last year has been extended by G M D'Ariano to quantum field theory, and now the free theory is derived by additional simple principles of information-processing (unitariety, linearity, homogeneity, and isotropy), without using relativity, but recovering the Lorentz covariance as emergent.

Several talks considered the possibility that the basic rule of quantum mechanics, the Born rule, can be violated. In particular, the papers by G Weihs and A Khrennikov attacked the problem from the two opposite sides. Weihs's paper presented the results of a experimental investigation, lasting over several years, to test a possibility that this rule is violated in the three slit experiment (as was indicated as a possibility by R Sorkin), while Khrennikov's papers presented the classical random field model reproducing approximately the probabilistic predictions of quantum mechanics, a model in which the Born rule appears only as an approximate law for calculation of probabilities. F De Martini presented a talk on a conformal field model based on Weyl's general relativistic 'dilaton' theory. The model reproduces the main predictions of quantum mechanics, including quantum correlations of the EPR–Bohm type violating the Bell inequality. This issue contains the paper representing the updated version of this theory. New approaches to the quantum measurement problem were presented in the talks of T Nieuwenhuizen and M Ohya. The results of experimental tests on a possible violation of another fundamental principle of quantum mechanics, the Pauli exclusion principle, were analyzed in the talk of C Curceanu, which also considered the possibility of performing measurements, using a similar experimental method, related to collapse models. The issue contains her paper devoted to these subjects.

We would now like to discuss papers presented at some special sessions of the conference.

We begin with the session 'Complementarity in Quantum Physics and Beyond,' which was organized by H Atmanspacher and A Plotnitsky. It could be noted, first, that one of the more curious features of the meeting was a resurgence of Niels Bohr's ideas. Of course, Bohr's ever-controversial interpretation of quantum mechanics, as complementarity, a particular version of the Copenhagen approach, and especially his debate with Einstein, which shaped the history of quantum mechanics and its interpretation, have been part of papers and discussions in Växjö conferences throughout their decade-long history. In this conference, too, the papers presented at the special session on 'Complementarity in Quantum Physics and Beyond' offers a comprehensive discussion Bohr's interpretation and the role and impact of his key concepts.

Overall, however, Bohr's thinking appears in this conference and in several papers in this volume in a different role, in particular, one reflecting an aspect of Bohr's thinking that would be significant regardless of whether one accepts Bohr's interpretation of quantum mechanics, or which side in the Bohr–Einstein debate one would take. It is Bohr's emphasis on the role, for him the irreducible role, of experiment and experimental technology in quantum versus classical physics (where this role could be neglected, at least ideally or in principle), and thus for our understanding of quantum foundations. This emphasis, it should be noted, goes beyond that on measurement, important as the idea of measurement was for Bohr. This emphasis is instead best understood as that on the irreducible role of experimental technology in the constitution of quantum phenomena. Indeed, Bohr sometimes speaks more broadly in terms of 'experience,' the experience of quantum phenomena defined by the role of experimental technology. This aspect of Bohr's argument is felt (sometimes when Bohr's name is not mentioned or even when the authors are not aware of Bohr's ideas concerning the subject) in a number of papers assembled here, including those presented at sessions other than that on complementarity, although both H Folse's and A Plotnitsky's papers expressly stress this aspect of Bohr's thinking as well. Among the conference participants, Bohr's emphasis on the role of experiment and experimental technology has been expressly important in A Khrennikov's recent work, including his paper presented here. While the paper offers the classical random field model reproducing approximately the probabilistic predictions of quantum mechanics, which is a sort of model not considered by Bohr, Khrennikov's argument is nevertheless in accord with Bohr's view of the role of experimental technology in the constitution of actually observed quantum phenomena.

Equally and even more significant is that Bohr's attention to experiment and experimental technology conforms exceptionally well to the uniquely distinctive feature of Växjö conferences among conferences devoted to quantum foundations which are nearly uniformly focused on technical, theoretical or philosophical aspects of quantum theory in isolation. By contrast, the Växjö conferences have been distinguished by the manifest presence of experimental physics alongside, and in the interaction with, theoretical physics and philosophy. This presence directs our attention, in accordance with Bohr's view, to the irreducible role of experiment and technology not only in physics itself (the point hardy needs mentioning) but also—and this does deserve a special mention—in our understanding of quantum foundations.

We now move to the session 'Quantum-classical hybrids,' organized by T Elze. Quantum-classical hybrid dynamics has been studied for several decades, a project motivated by questions concerning the foundations of quantum mechanics, as well as by practical needs arising from applying quantum theory to increasingly complex systems. The Copenhagen interpretation postulates the direct coupling between strictly classical degrees of freedom (apparatus) and quantum mechanical ones (object), without ever specifying how this takes place in a measurement 'interaction.'

The measurement process has been always under debate, but this debate has been revived recently with the development of new experimental techniques. Similarly, even with large-scale computing in hand, applications to, say, biologically relevant macromolecular processes still need reliable approximation schemes which would improve on the initial Born–Oppenheimer approach, which merely separated in an ad hoc way what are considered classical and what are considered quantum degrees of freedom.

Various quantum-classical hybrid dynamical schemes have been proposed since the earliest works of Sudarshan *et al* as can be witnessed in the references given in the papers invited to this special session. There has been an intermittent history of new schemes, new consistency checks and new problems observed, followed by no-go theorems. Most recently, a proposal by Elze (2012 *Phys. Rev.* A **85** 052109) claims to be successful in fulfilling the complete list of proposed consistency requirements. It has been independently shown by Buric *et al* (2012 *Phys. Rev.* A **85** 064101) that this theory can be understood as a limiting case of describing suitably constrained fully quantum mechanical coupled systems. There has also been an independent development, based on (stochastically extended) master equations, which seems to converge to a unique formulation, put forth by L Diosi.

The papers in this session reflect these lines of research and review them in detail. Most interestingly, all three papers are concerned with new applications of the respective hybrid schemes. Buric (Buric *et al*, this volume) and Diosi (Diosi, this volume) apply their respective approaches to the measurement problem, addressing the question of stochastically influenced yet definite measurement outcomes, as seen by a physicist's apparatus. It would be important to learn in future studies whether, or to what extent, these two approaches are equivalent. On the other hand, Elze and co-authors (L Fratino, A Lampo and H-T Elze, this volume) study a quantum-classical hybrid consisting of two physical q-bits coupled to a classical oscillator with emphasis on the dynamics of entanglement under various, possibly experimentally relevant conditions. These types of studies, considered together, may have important impact on the pursuit and, eventually, an interpretation of the vigorous experimental efforts to create and maintain (spacelike separated) quantum superpositions of mesoscopic objects. Does their quantumness remain recognizeable?

We conclude our overview of special sessions with the special session 'Quantum-like models outside physics: from cognition and information retrieval to economics and finances' which was organized by P Bruza, J Busemeyer, E Dzhafarov, E Haven and A Khrennikov. The session was a real success in establishing an interaction between the quantum information community and the humanities and social sciences (cognitive science, psychology, and even sociology and political science). During the last few years, the operational viewpoint concerning the mathematical formalism of quantum mechanics has been explored in these fields in order to describe statistics of observations. (The real experimental statistical data from, for example, cognitive psychology, exhibits non-classical features and cannot be described by the Kolmogorov model of probability theory). The plenary talk of J Busemeyer (a professor of cognitive psychology at Indiana University) on quantum(-like) modeling of the process of decision making was presented in front of about one hundred experts in quantum foundations and information and, in general, their reaction can be described as quite positive. This special issue also contains the review paper on applications of the quantum mathematical formalism in cognitive science written by J Busemeyer, Zh Wang, A Khrennikov and I Basieva which can serve as a good introduction to this new field of research.

It could be said, in closing, that the 2013 Växjö conference was an important event in the history of quantum foundations, once again, considering the subject from a joint perspective of theory and experiment. Numerous novel findings were presented, often resulting in intense exchanges representing different views and important critical insights. It was a successful continuation of annual conferences that began in 2000 and was a unique contribution to the continuing debate concerning quantum foundations.