Preface: Foundations of Probability and Physics - 6

This volume presents the proceedings of the International Conference Foundations of Probability and Physics-6 (FPP6) held in Växjö, Sweden, 13-16 June 2011. The organizing committee of the Conference included: V. Belavkin (University of Nottingham, UK), M. D'Ariano (University of Pavia, Italy), S. M. Fei (Capital Normal University, China), E. Haven (University of Leicester, UK), B. C. Hiesmayr (University of Vienna, Austria), G. Jaeger (Boston University, USA), A. Khrennikov (Linnaeus University, Växjö, Sweden), J-Å. Larsson (Linköping University, Sweden), M. Ozawa (Nagoya University, Japan), S. Stenholm (Stockholm University, Sweden), J. Tollaksen (Chapman University, USA). The conference was supported by Linnaeus University. The conference is part of the series of Växjö conferences on foundations of quantum mechanics (Bohmian Mechanics-2000, Foundations of Probability and Physics-2000, 02, 04, 06, 08, Quantum Theory Reconsideration of Foundations-2001, 03, 05, 07, 09), Advances in Quantum Theory-2010). The conference was primarily based on five special sessions:

General Questions of Quantum Foundations (organized by A. Khrennikov);
Novel Approaches to Quantum Theory (organized by V. Belavkin, M. D'Ariano, G. Jaeger, M. Ozawa);
Weak Measurements (organized by J. Tollaksen);
Fundamentals of QM tested in High Energy Physics (organized by B. C. Hiesmayr);
Quantum-like Models outside of Physics (organized by E. Haven and A. Khrennikov).

This is the 12th conference arranged in Växjö devoted to quantum foundations and quantum information, especially the clarification of fundamental questions—for previous conferences, see Lnu.se/forskargrupper/icmm/conferences. The Växjö series is the longest continuous series of conferences devoted to quantum foundations in the history of quantum mechanics. During these conferences, we were fortunate to have not only physicists (theorists as well as experimentalists), but also mathematicians and several philosophers discussing the foundations of quantum theory, especially in the light of recent developments of quantum information theory. Fundamental questions of quantum mechanics, especially information theory, quantum computing, cryptography and teleportation have continued to be central topics in this conference series.

Talks at the session "*General Questions of Quantum Foundations*" were characterized by a diversity of viewpoints as to the essence of quantum theory, its present state of development and its future. Novel and unexpected approaches to inter-relation between quantum and classical models were presented. The opening lecture of Francesco De Martini was about a new sub-quantum model of the classical field type (in the spirit of early Schrödinger) promising unification of quantum theory with general relativity. Some "beyond quantum" models were characterized by an essential departure from the traditional hidden variables approach. In particular, it was pointed out that contextuality, and hence non-objectivity, of observables are natural for some traditional models of classical field theory. A model of such a type, a classical field model (in the spirit of the later Einstein) reproducing the main predictions of QM, was proposed by A. Khrennikov. G. Adenier elaborated new attack to the Ekert protocol (as well as other standard protocols) based on one possible means of violating Bell's inequality by using pulses of classical light (exploring the unfair sampling loophole). The talk of H. De Raedt con-

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tained numerical simulation of the interference pattern in the two slit experiment on the basis of a purely corpuscular model. (In this model, the memory of detectors plays the fundamental role.) In this talk, it was also demonstrated (by numerical simulation) that Bell's inequality could be violated through the unfair sampling effect based on the presence of the time window in real experiments with entangled photons. Some participants (including leading experts in experimental research on quantum foundations) strongly criticized De Raedt's model as unphysical. Intensive discussions continued during the coffee-breaks.

Gregor Weihs analyzed the results of the recent experimental tests on violation of Sorkin's inequality for the tree slit experiment. Violation of this inequality was interpreted by Sorkin as an evidence of violation of the basic rule of QM, Born's rule. This interpretation was criticized by some participants, who pointed out that a violation of Sorkin's inequality is evidence of the complementarity of a few experimental contexts involved in the scheme of the three slit experiment. The latter viewpoint stresses the similarity between violation of Sorkin's and Bell's inequalities—at least if violation of Bell's inequality is by itself interpreted as an evidence of complementarity of experimental contexts corresponding to different pairs of orientations of polarization beam splitters involved in the EPR-Bohm experiment. Weihs also analyzed numerous technical problems arising in the realization of the three slit experiment; in particular, he pointed to the complicated problem of nonlinearity of detectors. Violation of Born's rule is also an important prediction of other "pre-quantum" theoretical models, e.g., the aforementioned classical field model of Khrennikov (pre-quantum classical statistical field theory, PCSFT). Besides attempts to go "beyond quantum," this session also contained a series of talks devoted to the fundamental and still unsolved theoretical problems of QM. One of such problems is the famous measurement problem. This problem was treated in a novel framework by T. Nieuwenhuizen, who explored (indirect) analogy between measurement and decoherence. He claimed that, finally, the measurement problem has been solved. (Similar claims have been also presented in some talks during previous Växjö conferences.)

The session "*General Questions of Quantum Foundations*" (and the conference in general) was noteworthy due to the large number of talks of experimenters working on testing of quantum foundations and development of quantum information theory, in particular, F. De Martini, A. Lvovsky, S. Polyakov, H. Rauch, F. Sciarrino, G. Weihs, and A. Zeilinger. The keynote speaker of the conference, Anton Zeilinger, presented a review on resent experiments of his research group in quantum optics. He emphasized that successful realization of the loophole free experiment on violation of Bell's inequality will play a fundamental role in clarification of foundations of QM.[1] He informed the participants about the progress in realization of such an experiment with the aid of ultrasensitive detectors (Tungsten-based Superconducting Transition-Edge Sensors). Besides presentation of the results of exciting experiments, Zeilinger's talk contained a brief presentation of *information interpretation of QM*. This interpretation emphasizes the role of information in QM; roughly speaking, neither particles nor fields but bits of

[1] We state again that at one of previous Växjö conferences A. Aspect considered the efficiency of detectors loophole as a technical problem playing a minor role in quantum foundations.

information are fundamental elements of QM. Of course, the most complicated problem of this approach is the treatment of information as the basic and irreducible element of theory. This problem was the subject of the intensive discussion after the talk. Although in general Zeilinger's interpretation of QM can be considered as a departure from the orthodox Copenhagen interpretation, Zeilinger's views match well the original Born's views to QM as an operational formalism describing extraction of information about processes in microworld by using macroscopic measurement devices. Among other important problems which may play crucial roles in resolution of quantum mysteries Zeilinger pointed to the usage of Aristotelian logic. This point induced a number of comments. E. Rosinger made a remark that some of the greatest breakthroughs in science in the last few decades were precisely in logic, and more precisely, there were no less than two such absolutely major and totally unprecedented ones: a) self-referential logic; b) inconsistent logic. (Amusingly, both of them were made in the 1980s due to theoretical computer science.) E. Rosinger speculated that these novel logical systems may play a role in quantum foundations.

Helmut Rauch gave a talk devoted to experimental research in neutron interferometry during the last 20 years, including recent tests of quantum contextuality. The latter topic attracted a lot of attention generating a hot debate concerning the meaning of quantum contextuality and inter-relation between contextuality and objectivity. H. Rauch also remarked (inspired by the talk of G. Weihs) that experimental studies of higher order interference in neuron interferometry might be used to study violation of Sorkin's inequality and Born's rule Theoretical problems of quantum information theory were discussed in a number of talk. S. M. Fei presented an approach for experimentally detecting quantum entanglement, by introducing a set of inequalities which are both sufficient and necessary for 2×3 mixed states. An explicit analytical lower bound of concurrence was obtained based on positive maps, which may detect entanglement better than some well-known lower bounds.

The geometry of quantum discord and the way of improving the capacity of quantum noisy channel were also discussed in this session. N. Watanabe M. Ohya developed a general approach to quantum conditional probability based on quantum lifting which is useful not only in quantum information theory, but even in application to cognitive science and micro-biology. This approach was also discussed in the talk of S. Iriyama. Chris Fuchs argued for a Bayesian approach to quantum mechanics, and against operational approaches. He also talked about his "golden standard" measurement: the SIC POVM, the existence of which is still only conjectured, and known only for a finite number of dimensions. M. Appleby filled in some of the mathematical details, explaining that quite sophisticated mathematics come into play, like Galois theory and theta functions. Ingemar Bengtsson also talked about a mathematical structure within quantum mechanics, but related to complementarity rather than Bayes' rule. In this case, the structure of Hadamard matrices is important, and Ingemar reviewed some of the progress in the field. Jan-Åke Larsson talked about quantum contextually as complementarity in its extreme form. He presented a contextual extension of Spekkens' (non-contextual) toy model, and discussed the cost of making such an extension. This cost is natural, he argued, since quantum contextuality is *the* distinguishing feature of quantum mechanics.

The special session "*Novel Approaches to Quantum Theory*" organized by Slava

Belavkin, Mauro D'Ariano, Gregg Jaeger, and Masanao Ozawa contained a number of talks on fundamental theoretical problems of quantum foundations. Previous consideration in Växjö foundations of physics meetings regarding the relationship between causation theory, particularly that of Arkady Plotnitsky and quantum mechanics was extended in this meeting by Jaeger, who argued that a causal account of the behavior of quantum systems can coherently be given within the context of the interpretation of quantum mechanics of Dirac and von Neumann if the quantum formalism is extended to include positive-operator-valued measures and effects as observables, as developed lately by Paul Busch, Pekka Lahti, and collaborators. In particular, the argument appeals to the notion of probabilistic causation as an extension of von Neumann's conception of mathematical causation in mechanics, which itself was intended to generalize aspects of the Laplacian notion to include quantum mechanics.

The axiomatization program of Quantum Theory of Mauro D'Ariano, initiated at the Växjö Conference of June 2005, reached its goal with a long Physical Review with Giulio Chiribella and Paolo Perinotti and the derivation of Quantum Theory from six principles about information processing. Their joint paper in these proceedings (presented by Paolo Perinotti) reviews this work, giving an easy-to-read illustration of the six principles. The Quantum Theory has nothing of "mechanics", it is the abstract theory of systems: the mechanics should be derived from the quantum theory of fields. With this motivation, the informational/operational axiomatization program continues now with Quantum Field Theory, with the new work of D'Ariano on a Quantum Cellular Automata formulation of the theory, solving the Feynman problem of the qubit-ization of Fermi fields, and entering the meanders of space-time, with the mechanics emerging from pure information-processing. In it, one is shown how "particles" could materialize from the quantum computation, and which phenomena one might expect at the tiny Planck scale.

The special session "*Fundamentals of QM tested in High Energy Physics*" organized by Beatrix C. Hiesmayr discussed a new emerging research field which adresses very fundamental questions of quantum mechanics and relates them to very fundamental questions in particle physics. Quantum mechanics has existed for more than 100 years, but some long-standing debates are still alive and waiting for a solution. In a different field, in particle physics, experiments are achieving ever higher precision such that the borderline of known physics will be reached. Combining both fields and aiming to tackle some of the most fundamental questions of quantum mechanics and to relate them to the most fundamental questions in particle physics seems obvious. In last year's conference a puzzling result was presented, i.e. that a Bell inequality, detecting the non-locality of quantum mechanics, is in contradiction to the observed asymmetry between matter and antimatter explored in particle physics. This year's conference devoted a session to this new emerging field of testing "*Quantum Mechanics in High Energy Physics*." A well balanced mix of two theoreticians (Nikolaos Mavromatos, Beatrix C. Hiesmayr) and three experimenters (Antonio Di Domenico, Antonio De Santis, Catalina Curceanu) covered various tests of foundations of quantum mechanics in systems of high energy physics and of nuclear physics.

The session opened by addressing the potential role of quantum gravity on an induced intrinsic violation of the CPT (Charge conjugation, Parity, Time reversal) symmetry.

This could result into a perturbatively weak modification of the Einstein-Podolsky-Rosen (EPR) correlation of entangled neutral kaons. The DAΦNE collider in Frascati (Italy) is designed to copiously produce pairs of neutral kaons. They are entangled in the strangeness number, i.e. of being a kaon K^0 or an antikaon $\bar{K}^0$. The strangeness property is oscillating in time, i.e. starting at time $t = 0$ with a kaon state K^0 the probability to find at a later time point an antikaon $\bar{K}^0$ is nonzero. These systems are decaying, which at one hand side opens up new possibilities, due to the different measurement procedures involved, and on the other hand implies challenging differences compared to stable systems.

In the next talk, the leading convener of the quantum tests of the KLOE detector at the DAΦNE machine introduced the unique and clean environment in which various features of these entangled kaons can be exceptionally studied. He and the following speaker presented also first results of tests of the entanglement in the kaonic system which show the high sensitivity to possible new effects (e.g. decoherence introduced by various sources such as quantum gravity, Lorentz symmetry violation, CPT violation ...). Consequently, one can expect that in future several theoretical proposals about foundations of quantum mechanics will be put to test by sophisticated experiments.

The fourth talk demonstrated that fundamental tests of quantum mechanics are also feasible in atom and nuclear physics, in particular to search for small violations of the Pauli exclusion principle. This spin-statistics connection is tightly embedded in the very essence of modern field theory. Experimental results from the VIP experiments in the Gran Sasso National Laboratory were presented and discussed, together with their theoretical implications and future perspectives. A similar method can also be used to check some predictions of collapse models, in particular the spontaneous X ray emission by electrons. A feasibility study was presented, showing that, indeed, the search of X rays gives the strongest limit on a possible collapse. Last but not least, the information theoretic content of observables typically measured in such collider experiments was discussed; it demonstrates the challenging differences to other quantum systems but also enlightens the huge potential these systems have in answering the most fundamental questions we still have.

The special session entitled "*Quantum-like Models outside of Physics*" organized by Andrei Khrennikov, Emmanuel Haven and Bart D'Hooghe had a series of papers devoted to an area of research which is maybe, at present, less well known. Quantum mechanical techniques can be shown to have potential use in areas like the humanities and the social and biological sciences. The papers in that special session revolved mostly around four topics: i) how quantum mechanics can be used to model glucose effects in bacteria; ii) how quantum mechanical techniques can be used in decision making; iii) how quantum mechanics and the humanities can connect and finally iv) how quantum mechanical techniques can be used in financial asset pricing. In the presentation of Khrennikov, Tanaka et al., it was shown that the concept of probability interference was of prime importance in explaining E-coli growth as the law of total probability can not be used to explain such growth. The same concept of probability interference can also be used to explain experimentally confirmed decision making anomalies. This was discussed in important detail in the two presentations by Khrennikov, Asano et al and the talk by Kitto and Bruza. A primer on the connection between science, literature,

and life was made in the presentation by Plotnitsky. Finally, the papers by D'Hooghe et al.; Sozzo; and Haven et al. all discussed how quantum structures could be used in a variety of economics based applications. For instance, in Haven et al.'s presentation the role of the wave number was discussed in an economics context. We hope that this special session can provide for the impetus for similar special sessions at future FPP conferences.

We hope that this volume will be useful for experts working in all domains of quantum physics and quantum information theory: theoreticians, experimenters, mathematicians, philosophers. The session on quantum-like models may be interesting for mathematically oriented psychologists, economists, experts in theory of decision making and cognitive science, micro-biology and genetics.

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