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EDITORIAL

Paul Busch: At the Heart of Quantum Mechanics

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This special issue of *Foundations of Physics* commemorates the scientific work of Paul Busch (1955–2018), with contributions from his students, friends and collaborators. The title reflects Paul's research field and his attitude to it: foundations of quantum mechanics investigated with full heart.

In the University of York web pages we may read Paul's own overview of his research:

> My research interests lie in the interface between physics, mathematics and philosophy, centering around questions on the relationship between quantum and classical physics, relativistic quantum measurement and quantum information theory.
>
> A focus in recent years has been the subject of quantum uncertainty, notably the theory of approximate joint measurements of incompatible observables and the study of associated measurement uncertainty relations, a subject of an ongoing scientific controversy.

Paul's first paper, *On the behavior of an oscillator clock near the singularity of a gravitational field*, appeared in 1980 and was based on his 1979 master thesis entitled, *On the empirical relevance of proper time in a gravitational field with singularity*, (in German). The paper, *Measurement uncertainty relations: characterising optimal error bounds for qubits*, written with Tom Bullock, turned out to be Paul's final contribution. Paul's scientific work consists of a good 150 presentations, including 92 peer reviewed journal papers and three co-authored monographs.

Apart from his first paper, Paul's work was devoted to foundations of quantum mechanics, covering topics from quantum measurement theory and quantum structures to his cherished ideas on the concept of unsharp reality.

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Paul's doctoral thesis, *Unbestimmtheitsrelation und simultane Messungen in der Quantentheorie*, Cologne 1982, gave direction to much of his later work. This is most appropriate also in view of the fact that Paul was a scientific grandson of Werner Heisenberg. In fact, almost one third of Paul's published work deals more or less directly with this topic of measurement uncertainty.

The thesis called into question the exclusive validity of the statistical interpretation of the uncertainty relations and it goes on to justify an individualistic interpretation, formulated by means of the concept of unsharp observables through a joint measurement model for position and momentum. Here we see Paul's first attempt to analyse carefully the two aspects of the uncertainty relations, now known as the preparation and the measurement uncertainty relations.

The beginning of Paul's scientific career coincided with two important scientific developments, the emergence of a generalized or operational framework for quantum mechanics, and the advances on single-object experimental quantum physics.

Indeed, from late 1960's and 1970's onwards it slowly became clear that the traditional (text book) formulation of quantum mechanics was unnecessarily restrictive, especially in describing measurements. In particular, the use of positive operator measures instead of the more traditional spectral measures, or selfadjoint operators, broadly expanded the scope of quantum mechanics and it gave the tools needed to describe realistic experiments and to go beyond the typical 'no-go' scenarios in many conceptual questions.

From mid 1970's onwards the advances in experimental quantum physics slowly allowed the possibility of performing measurements on single quantum objects, first with neutrons, then with photons and electrons and later also with atoms and molecules. This not only allowed researchers to carry out the extreme tests of quantum mechanics, hitherto considered as thought experiments, but it also greatly increased the motivation to develop an individual interpretation of quantum mechanics, one of Paul's favourite motifs.

The arising of quantum information science in the 1990's is a further related development. This not only increased interest in foundations of quantum mechanics opening new viewpoints on quantum measurements as information processes but it also slowly changed the rather openly hostile 'shut-up and calculate' attitude of a typical theoretical physicist to foundational studies so that from 1990's onwards it became more or less acceptable to work on foundations of quantum mechanics.

Unsharp observables, as positive operator measures, were a key tool in Paul's analyses of the foundational problems of quantum mechanics. In his own words:

> My current main research interest is the development of the operational tools of quantum measurement theory (observables as POVMs, quantum operations), their application to the solution of conceptual problems and the modelling of practical measurement schemes.

The conceptual problems Paul addressed with these operational tools include questions like:

– how much unsharpness needs to be introduced to a pair of complementary observables to allow their joint measurements, or at least joint tests, what are the

physically interesting measures of approximation and degrees of unsharpness of quantum observables, and what are the resulting approximate joint measurability regions of incompatible observables;
- how stable are the arguments like the Einstein–Podolsky–Rosen–Bohm paradox, the quantum measurement problem, or the limitations on measurability posed by the conservation laws against introducing measurement inaccuracies in the form of unsharpness in the arguments;
- which properties of measurements are needed to develop a consistent notion of unsharp reality together with the adequate notions of sharp and unsharp properties and their joint properties.

The collection of papers in this special issue pays tribute to Paul's scientific work and addresses some of the deep problems that guided Paul in his investigations at the heart of quantum mechanics.

The paper of Werner and Farrel focuses on current quantum uncertainty research and provides a refreshing reading of Heisenberg's famous 1927 paper from the eyes of modern-day theoretical physicists. The paper of Carmeli, Heinosaari, Myiadera, and Toigo employs the general framework of Galois connections to investigate the relation between noise and disturbance. The paper of Kiukas, Lahti, Pellonpää and Ylinen studies complementary observables and offers some new characterizations of this concept. The paper of Carmeli, Cassinelli, and Toigo characterizes the extremality of a class of pairs of noisy MUB observables in the convex set of all pairs of compatible quantum measurements. The paper of Loveridge and Miyadera presents a derivation of local Heisenberg evolution under the constraint of global time translation invariance using the methods developed in their previous works with Paul.

In Paul's view, the need to extend the notion of an observable from a spectral measure to a positive operator measure was dictated by both practical and conceptual demands. Among other things, this opened the possibility of investigating the problem of space localization for a photon as studied in the paper of Beneduci and Schroeck. It also led to Schmidt's contribution on characterizing extremal observables, including sharp ones. Deriving the Born rule, which expresses the statistical duality between states and observables, may also be seen in a new light with the generalized notion of an observable. The paper of Wright and Weigert builds upon Paul's previous work in this subject. On a more abstract level, the study of quantum structures is another path opened by the operational framework for quantum mechanics. The paper by Dvurečenskij is an example in this direction.

The minimal interpretation of quantum mechanics was a natural starting point for some of Paul's studies, but he did not stop at that level. Instead, he wanted to take further steps and investigate the possibilities for an individual interpretation of quantum mechanics. The papers of Dieks, Gudder and Jaeger all share Paul's desire to go beyond the purely statistical interpretation. Moreover, the related questions of the quantum-classical connection covered by Stulpe, was one of Paul's interests.