

Foreword

A central insight of modern quantum physics is that randomness in the quantum regime has a different nature than in the classical world. In classical theories such as statistical mechanics randomness is explained by missing knowledge on the initial conditions or physical processes. In the quantum regime, however, this view can become problematic. If randomness is caused by ignorance, one assumes that there are additional parameters which determine the process and the randomness disappears for observers knowing these parameters. John Bell, however, showed in 1964 that models with hidden parameters must be non-local, if they should reproduce the predictions of quantum mechanics. The corresponding violation of Bell's inequalities has been observed experimentally, ruling out certain types of hidden variable models.

There is a second no-go theorem for hidden variable models, which is known as the Kochen Specker theorem. In short, it states that quantum mechanics cannot be reconciled with classical models that are noncontextual for compatible observables. Here, compatible observables are observables that can be measured simultaneously or in any order without disturbance, and noncontextuality means that the value of an observable does not depend on which other compatible observable is measured jointly with it. The phenomenon that quantum theory goes beyond noncontextual theories is called quantum contextuality and it also has been recently observed with trapped ions, polarized photons or nuclear magnetic resonance.

When testing quantum contextuality in experiments, a sequence of several measurements is carried out on a single quantum system. Here, a problem arises: the observables should not disturb each other, but due to experimental imperfections this will not be the case. So

one has to analyze the effects of this errors on the conclusions drawn from the experimental data and this is exactly what the current thesis from Jochen Szangolies is about. In this thesis, several types of noise models for experiments are discussed. In principle, already small amounts of noise can nullify the conclusions about a contextuality experiment. But, as shown in this thesis, with the help of modified Kochen Specker inequalities one can still rule out large classes of hidden variable models. The proposed modification can easily be implemented, as it only requires measuring permutations of the quantum observables. Therefore, the thesis of Jochen Szangolies represents a valuable contribution to current discussions and I am happy that it appears in the Springer BestMasters book series.

Otfried Gühne

Preface

QUANTUM theory, as formulated in the first three decades of the last century, has long since developed an almost proverbial reputation for being weird, counterintuitive, or even flat-out impossible to understand. The source of this is certainly to be found in the ways in which it differs from classical physics, which until the advent of quantum theory seemed to carry the promise of bringing the world within our grasp—that is, providing a clear and intelligible picture of the mechanisms according to which planets and atoms alike trace their orbits. It is the upset of such intuitions, honed by our intimate familiarity with the macroscopic, that lends its mysterious air to quantum theory.

This book constitutes neither an attempt at dispelling the mysteries, nor does it try to reconcile them with pre-quantum expectations. Rather, its aim is to contribute to the more modest programme of making precise where and how quantum physics diverges from classical expectations. The—albeit reluctant—founding fathers of said programme are Albert Einstein, Boris Podolsky, and Nathan Rosen, who in their seminal article “Can Quantum-Mechanical Description of Physical Reality be Considered Complete?” [2] were the first to raise the issue of the completeness of quantum theory, that is, the question of whether it provides a full account of the underlying physics, or whether it has to be augmented by additional quantities (which have since become known as ‘hidden variables’) to furnish such a description.

Their intent was, with an ingenious argument, to establish that there indeed are quantities that quantum mechanics in its standard form does not account for, and thus, to show that there must be some deeper theory capable of describing this more fundamental layer.

They could not have anticipated that their argument would ultimately, via the mediation of John Bell, lead to very stringent constraints on the possibility of such a more fundamental description: as Bell showed [7], if we are to entertain the possibility of definite quantities left unaccounted for by the quantum formalism, then these quantities must be able to instantaneously influence one another across arbitrary distances, if the resulting theory is to be capable of duplicating all quantum mechanical predictions. The experimental confirmation of these predictions then was what cemented the importance of Bell's theorem in the corpus of scientific knowledge.

The present work is concerned mainly with a related, though substantially different theoretical result, typically known as the Kochen-Specker theorem after Simon Kochen and Ernst Specker [23]. Like Bell's, the theorem by Kochen and Specker considers the completeness of quantum mechanics with additional quantities, and derives constraints on the nature of these quantities. Unlike Bell's theorem, experimental assessment of its consequences is less straightforward. The problem is, in a nutshell, that the relevant notion of noncontextuality—roughly, the persistence of physical quantities independently of the experimental setting—is well defined only for ideal measurements, and ceases to apply in a more realistic setting. The resulting obstruction to the experimental testability of the Kochen-Specker theorem is the main topic of this monograph.

The work contained herein was accepted as a diploma thesis at the University of Siegen, and was completed under the tutelage of Prof. Dr. Otfried Gühne, for whose guidance, experience, and not least for the opportunity of working within his group on this fascinating topic I could not be more grateful. An equal measure of thanks is due to Dr. Matthias Kleinmann, who took me under his wing as my immediate supervisor, and as such, proved to be an invaluable source of insightful ideas, as well as a formidable foe for the sillier ones.

I have also benefitted greatly from discussions with and the accumulated knowledge of the other members of the Theoretical Quantum Optics Group at Siegen, among them my three office mates Dr. Mazhar Ali, whose passion for knowledge and insight served as a reminder

of why I had myself chosen this path in times when going forward got difficult, Marcel Bergmann, whose interests extend far beyond his area of specialization and with whom I fondly remember watching the announcement of the Higgs boson's discovery, and Dr. Costantino Budroni, whose expertise on the topic of quantum contextuality, and whose rare gift to see directly through to the core of an idea, and identify the misconception it rests upon, I have greatly admired. I am furthermore thankful for having had the opportunity of working with Dr. Martin Hofmann, even beyond my time at Siegen, Dr. Tobias Moroder, not just for having the good grace to let me win the occasional game of billards, and Dr. Sabine Wölk.

Additionally, I would be remiss not to express my thanks towards Prof. Dr. Dagmar Bruß, for giving me a new academic home at the Quantum Information Group at the university of Düsseldorf, and who graciously allowed me to take some time to polish this manuscript up for publication. Finally, for comments on this manuscript, I warmly thank Michael Epping.

My trajectory up to this point has not always been a smooth one, and thus, a very special thanks is also due to my family, starting with my father, Bernhard, for never losing faith in me and supporting me through difficult times, no matter what, and to my mother, Barbara, who in many more ways than I am probably aware of provides both the origin of my frame of reference and the initial conditions that serve to define my path in life, and whose too early loss I still deeply mourn. My sisters, Inka and Gisa, I first and foremost wish to thank for, through their lives, giving me an example showing that it can be done after all. You have had much more of an impact on my life than you might know, and I genuinely look up to you.

Last, but by no means least, I want to thank my fiancé, Constance Bartz. Her commitment, love, and support are, more than anything else, what made this work possible—but her bravery in accepting my marriage proposal is what has made me a happy man.

Jochen Szangolies

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The Problem of Compatibility

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