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Exploring Quantum Foundations with Single Photons

Doctoral Thesis accepted by
The University of Queensland, Australia

Springer

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Supervisor's Foreword

Questions about the foundations of quantum mechanics are as old as quantum mechanics itself, with famous theoretical and philosophical debates captured in the letters and papers of the fields' founders. Experimental investigations, however had to await the post-war florescence in experimental techniques and technologies. Consequently, experiments aimed at exploring issues in quantum foundations only began in my lifetime, a notable early example being the Bell inequality measurements by Stuart Freedman and John Clauser in 1972. At that time there was a considerable stigma in doing such experiments: Pat Thaddeus, Clauser's Ph.D. advisor wrote letters of reference that said "Don't hire this guy if there's any chance that's what he's going to do, because it's all junk science." Clauser has said "I was sort of young, naive, and oblivious to all of this. … I had yet to recognize just how much of a stigma there was, and I just chose to ignore it. I was just having fun, and I thought it was interesting physics."

Fortunately this stigma has long since faded. The last three decades have seen the fields of quantum optics, atom optics, and quantum information all providing considerable impetus—conceptual, theoretical and experimental—into the study of quantum foundations.

Gentle reader, whether you approach this thesis as a complete novice or an expert in quantum foundations you are in for a treat: Martin's opus serves both as a superb introduction to quantum foundations research, and as a masterful account of his own original—and significant—contributions. You are about to embark on a journey that encompasses quantum information; quantum correlations, games and paradoxes; the long-standing question as to whether the quantum wavefunction is really real; the role of causality in quantum mechanics; and a fresh look at joint-measurement uncertainty. One of Martin's thesis examiners—themselves a leading quantum experimentalist—enthused that Martin's “…comprehensive discussion is essentially unmatched by anything I have seen elsewhere.” I completely agree and feel sure that you hold in your hands a thesis that will be, not too many years from now, recognised as the nucleus of a classic textbook. So don’t waste any more time reading this foreword, but dive on in—you will enjoy every minute.

Brisbane, Australia
May 2017

Andrew G. White

Abstract

Quantum mechanics is our most successful physical theory and has been confirmed to extreme accuracy, yet, a century after its inception it is still unclear what it says about the nature of reality. In this thesis, I explore some of the foundational questions which are central to our understanding of quantum mechanics using single photons as an experimental platform. Three experiments form the core of the thesis, studying, respectively, the role of reality, causality, and uncertainty in quantum mechanics. These experiments shed light on decades-old questions that have previously been thought to be outside the realm of experimental physics. The results contribute to our understanding of the structure of quantum mechanics, and reveal novel aspects of phenomena that were believed to be well understood. Starting out as a fringe discipline, the field of quantum foundations has developed into an influential area of research. It is now becoming possible to turn many of the foundational questions in quantum mechanics from topics of philosophy into topics of physics. Subjecting these questions to rigorous experimental tests, the field is making progress in the quest for understanding our best physical theory.

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I would also like to acknowledge my theory colleagues Cyril Branciard, Eric Cavalcanti, Fabio Costa, Howard Wiseman, Ivan Kassal, Tim Ralph, and Gerard Milburn, for inspiring discussions. Special thanks to Cyril for making sure I am precise with every detail. I would like to thank all the philosophers I was privileged to work with, especially Sally Shrapnel and Peter Evans, for introducing me to the ways of philosophy of physics.

My sincere apologies go to Glen Harris and David McAuslan for dragging you out of bed for our 6:00 am climbing sessions. You and all the other friends I made here made my time.

Special thanks go to Nina for her support throughout my studies, and for dragging me out of the lab every now and then.

Finally, I am extremely grateful for having such a loving and supportive family. My grandparents for their loving nature and countless childhood adventures. My late grandma, unbeatable in her card games, for her unique, sarcastic sense of humour that will always be remembered. Mum and dad, for their unconditional support, great advice, and encouragement. My sisters, who I can always count on, and my cousin, who is always up for a good time.

Contents

Preamble

In 1900 Lord Kelvin delivered a lecture at the Royal Institution of Great Britain at a time where the general sentiment was that physics was mainly understood and the only thing left was to perform more precise measurements. In this lecture, Kelvin pointed out that "the beauty and clearness of the dynamical theory, which asserts heat and light to be modes of motion, is at present obscured by two clouds". These two clouds referred to the failure of the Michelson-Morley experiment to reveal the luminiferous aether, the hypothetical medium through which light travels; and the fact that the radiation laws of the time made unphysical predictions about the radiation emitted by a black body, known as the UV catastrophe. Just five years later, Kelvin's two clouds gave rise to the theory of relativity and quantum mechanics, respectively—two theories which caused a radical change in our understanding of the physical world and went on to become the most successful physical theories. Today, quantum mechanics is the basis of all of modern physics with the notable exception of gravity, which remains the territory of relativity and is notoriously difficult to give a quantum description of. Over the last decades the counterintuitive predictions of quantum mechanics held up in every experimental test and were confirmed to unprecedented accuracy. Yet, a century after its inception, the cloud over the interpretation of quantum mechanics is yet to be lifted.

There are two parts to any physical theory: the mathematical formalism, which describes how the theory works, and the physical interpretation, which connects it to the real world. While the former is fixed for a given theory, the latter can, and does in general evolve. In classical mechanics these two go hand-in-hand. There is a parameter x, which is interpreted as the position of a particle, and there is a differential equation which describes how x changes over time, that is, how the particle moves through space and reacts to external forces. As physical theories become more advanced, this one-to-one correspondence breaks down. For example, Maxwell's theory of electromagnetism was initially interpreted as describing stresses and movements in an elastic medium, the luminiferous aether, which carries light waves. This widely accepted interpretation turned out to be untenable after the famous Michelson-Morley experiment failed to discover the aether and its very existence was difficult to maintain in the light of other results such as the theory of relativity. Today it is understood that the aether does not exist and that electromagnetic waves do not need a medium to propagate. Despite this drastic change in interpretation, however, the mathematical formalism in terms of the Maxwell-Heaviside equations remained unchanged and makes the same experimental predictions.

Quantum mechanics takes this interpretational ambiguity to an embarrassing new level, with not two but over a dozen actively used interpretations. Much of the incentive for this development stems from attempts to finding a satisfactory resolution of the quantum measurement problem. The central object of the theory, the wavefunction, or quantum state, is used to describe and make predictions about any kind of quantum system. According to quantum mechanics, the wavefunction evolves continuously and deterministically with the Schrödinger equation, which means that knowing the starting conditions, one can perfectly predict the future state of the system. In the course of such an evolution the wavefunction typically ends up in a quantum superposition and the system is, loosely speaking, in multiple states at the same time. Yet, in an experiment we always observe definite outcomes. This is captured by the so-called projection postulate, which asserts that, in a measurement, the wavefunction abruptly collapses probabilistically into one of the possible outcomes. The problem, however, is that quantum mechanics provides no clue as to what counts as a measurement and what does not, neither does it explain why a particular measurement outcome occurs. This leaves plenty of room for interpretations, ranging from emphasizing the role of the observer in creating the measurement outcome, to considering the collapse as a physical process that happens all the time without any measurement, to rejecting the collapse completely and treating every branch of the superposition state as an alternate reality.

Narrowing down the list of interpretations holds the key to a better understanding of quantum mechanics, yet deciding between them is difficult in practice. Besides pure interpretations, there are in fact a few theories, which modify the mathematical structure of quantum mechanics. These theories make predictions that differ from quantum mechanics and are thus, in principle, subject to experimental tests with future experimental capabilities. The vast majority, however, are interpretations which supplement the mathematical formalism of quantum mechanics with a wide range of physical narratives. These interpretations make largely the same predictions as quantum mechanics, but as in the case of the luminiferous aether, this does not necessarily mean they are immune to experimental tests. Besides striving for a better understanding of our best physical theory, research into quantum foundations and interpretations of quantum mechanics has inspired the development of some revolutionary technologies. Quantum computing, for example originated in David Deutsch contemplating over the many worlds interpretation, and quantum cryptography is rooted in John Bell's study of local-causal hidden-variable theories for quantum mechanics. With applications such as these, foundational research has been pivotal for the development of quantum information theory, which in turn provided a new language and mathematical formalism to rigorously address some of the central questions in quantum foundations. Hence, apart from the desire for our best physical theory to provide more than just predictions, developing a deeper understanding for the theory is crucial for developing it further and harnessing its full potential.

What to Expect

The core of this thesis is three experiments, studying the role of reality, causality, and uncertainty in quantum mechanics, which are presented in Chaps. 4–6, respectively. Each of these chapters is largely self-contained and readers with a strong background in quantum information, quantum foundations and quantum photonics may wish to skip directly to these chapters. Readers less familiar with these fields will find introductions to the relevant technical concepts, notations, and mathematical background used throughout the thesis in Chaps. 1–3.

In Chap. 1 I introduce the main concepts and notions of quantum information theory, which forms the technical basis for the rest of the thesis. This includes discrete-variable quantum states, processes and measurements, as well as the experimental implementation of these using single photons and linear optics.

In Chap. 2 I discuss quantum tomography, which is a central tool for calibrating, testing and verifying quantum experiments. This chapter also includes the first new results of the present thesis, where we demonstrate a new tomography technique based on quantum superchannels. This technique enables a complete characterization of the evolution of a quantum system even when it is coupled to, and initially correlated with an environment, in which case standard methods fail.

In Chap. 3 I introduce a number of central concepts and ideas relevant to the study of quantum foundations. This includes quantum correlations, and how correlation polytopes can be used to characterize them and find Bell-type inequalities. I also briefly touch upon the search for a physical principle that could explain why quantum correlations are not as strong as relativity allows. This is based on an experimental simulation of post-quantum correlations. The rest of the chapter focuses on contextuality—which is widely accepted as the central feature that differentiates quantum theory from classical theory with an epistemic restriction—various quantum paradoxes, and weak values.

Chapter 4 is devoted to the role of the quantum wavefunction within interpretations of quantum mechanics. Despite being the central object of the theory and of crucial importance for making predictions, it remains unclear whether the wavefunction corresponds to physical reality or is rather a representation of our incomplete knowledge of that reality. The core of this chapter then discusses an experiment, where we showed that the latter interpretation cannot fully reproduce quantum predictions.

Chapter 5 discusses the role of causality in quantum mechanics. I first introduce the causal modeling framework as a rigorous mathematical basis for this question. I then introduce a new causally motivated decomposition of the assumptions behind

Bell's theorem, and an experiment, where we demonstrated that allowing for superluminal communication of measurement outcomes is not sufficient to explain quantum correlations in terms of classical cause-and-effect relations.

Chapter 6 focuses on a widely overlooked aspect of Heisenberg's uncertainty principle. Contrary to widespread understanding, this central principle not only limits how well two incompatible observables can be prepared on a quantum system, but also how accurately they can be jointly measured. I then present two experiments, where we test the optimal tradeoff in measurement accuracy in a joint approximation of two incompatible measurements on quantum systems.

Finally, Chap. 7 concludes with a summary and discussion of the results presented in this thesis, and directions for further research.