Preface

Seventeen years ago the Center for Frontier Sciences at Temple University was launched with an intriguing workshop entitled *The Philosophy of Quantum Theory*. The event, chaired by our first director, Gideon Carmi, brought together leading physicists and philosophers to address this issue. Participants included Roger Penrose, Abner Shimony, Bernard d'Espagnat, Yakir Aharanov, Basil Hiley and the late David Bohm, as the keynote speaker. In looking back, one of the workshop's greatest achievements was to establish a dialogue on quantum mechanics among these scientists, a dialogue that is still continuing today.

Quo Vadis Quantum Mechanics? is a further brainchild of the Center for Frontier Sciences. Some of the contributors to this volume were present at the first workshop, whilst others were still unknown students at that time. All contributors to the present volume were initially invited to a closed workshop/brainstorming at the Center. During that gathering, they each presented their ideas and exchanged views on what they believe are today's greatest challenges and open questions in quantum mechanics. The informal presentations were followed by lively round-table discussions. Subsequently all authors have written down, expanded and revised their contributions. To add extra spice to the book, the editors have included transcripts of some highlights of the round-table discussions. Springer did the rest – and their best.

Comparing this volume with some transcripts of the 1987 workshop at our disposal has made us very aware of the enormous progress that theoretical and experimental quantum physics has undergone during this period.

When Richard J. Fox founded the Center in 1987, he stated that leading scientists worldwide working on frontier scientific issues needed the opportunity to come together and exchange information on their work and brainstorm on their topics. The Center continues to uphold its founder's vision. Let us all keep in mind that the frontier scientific issues of the present are often the mainstream science of the future.

Acknowledgements

In addition to the many eminent scientists whose works appear in this book, it is only fitting that we acknowledge those who assisted behind the scenes in producing this book. We wish to thank the managing editor of *Frontier Perspectives*, Mary Huebner, the assistant editor of *Frontier Perspectives*, Meghan Nolan, the Center's coordinator, Kristine Norton, and Robert Flower and David Stein, who serve on the Center's advisory and editorial boards. We are most grateful to Angela Lahee from Springer-Verlag who guided and supported us throughout this entire production. The tireless efforts of these fine people played a vital role in producing this publication. Last but certainly not least we wish to acknowledge Richard J. Fox and his foundation for funding the workshop that provided us with the opportunity to bring all our honorable guests together and develop this fine book.

Temple University,
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Contents

1 What Is the Measurement Problem Anyway? Introductory Reflections on Quantum Puzzles

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"Can the quantum-mechanical description of physical reality be considered complete?" It is perhaps not coincidental that this question, the title of Einstein's famous onslaught on quantum mechanics [1], was echoed verbatim in the title of Bohr's reply [2]. Although Bohr opted for a "Yes", today even his ardent followers (see Wheeler below) believe that quantum mechanics is not the last word.

Someday, we all believe, a new theory will revolutionize physics, just as relativity and quantum mechanics did at the dawn of the 20th century. It will include its two parent revolutions as special cases, just as classical mechanics has been comfortably embedded within relativity theory and less comfortably within quantum mechanics. What this theory will tell us about the nature of reality is anybody's guess, but John Wheeler has vividly captured its most immediate feature [3]:

> Surely someday, we can believe, we will grasp the central idea of it all as so simple, so beautiful, so compelling that we will say to each other, "Oh, how could it have been otherwise! How could we have been so blind so long!" (p. 28)

Greenberger, however, has much more sobering reflections [4]:

> Most physicists believe that, had they been around at the birth of relativity, they would have been able to instantly appreciate its radical elements. But my own experience indicates that if Einstein were to send his paper to *Physical Review* today it would have almost no chance at all of being published. "Highly speculative!" would be the referee report, a death shell to any paper. He would have to append it to an article on string theory, or some other fad, and hope it wasn't noticed. (p. 558)

We can only hope that Wheeler is correct and Greenberger is exaggerating, and that the new theory is not already laid down in some yellowing manuscript concealed in some embittered author's drawer. Let us also hope that the theory will be published within our lifetime.

How would the puzzles of quantum mechanics fare in that revolution? Before indulging in some guesses, which are naturally bound to disclose personal biases, let us recall the puzzles themselves. There are three main questions [5]:

- **Wave–Particle Duality.** Subject any particle to an experiment set to measure waves and it will manifest unmistakably undulatory properties. Perform on it an experiment designed to measure corpuscular properties and you will end up with a particle. Both results are equivocal – and mutually exclusive. As Feynman [6] aptly remarked: the double-slit experiment (where this dual nature becomes most visible through the interference pattern) contains the core of the quantum mechanics mystery. The uncertainty principle is the general formulation of this duality, allowing only one out of a pair of physical values to be measured with arbitrary accuracy.
- **Quantum–Classical Limit.** The extraordinary predictions of quantum mechanics, such as the above interference effects, hold perfectly for particles, but fail flatly for macroscopic objects. In other words, superposition is observed in particles but never in cats, even though the latter are made of the former. Where does the jurisdiction of quantum mechanics end? Atoms also exhibit interference, and so do large molecules, although the experiments become difficult with the size of the interfering objects. Does classical mechanics simply take over at some scale [7] or is it only technological limitations that do not yet allow us to demonstrate the quantum behavior of larger objects (see Chap. 3)? This is the 'measurement problem', arising every time the properties of a particle are amplified to macroscopic extent.
- **Non-Locality.** The wavelike behavior of a single particle entails that, in order to obey conservation laws, distant parts of the wave function must instantaneously affect one another upon measurement. And indeed the violations of Bell's inequalities [8] manifest instantaneous effects of one particle's measurement on the state of another, entangled particle, regardless of the distance separating them. Quantum mechanics thus defies the spirit, if not the letter, of relativistic law.

It is such puzzles that herald a scientific revolution. Yet despite repeated promises made by superstring and other theories, no such revolution has yet appeared. Still, although we cannot know the theory itself, Wheeler's poetic sentiments about how we would *feel* upon encountering it reflect sound scientific intuition: the theory will probably *appeal* to us as true. We can therefore – and in fact, we should – lay down our expectations. It may prove to be a constructive exercise. So, based on the past experience of science, our long-anticipated theory should manifest the following qualities:

- **Beauty.** Every scientist is familiar with the aesthetic pleasure one experiences upon understanding a profound theory. An entire realm of facts becomes organically integrated, and, at the same time, simpler. Seemingly-accidental effects, which the earlier theory regarded as 'just being that way', turn out to be meaningful, even imperative. Hence, the theory that we yearn for should likewise render the quantum peculiarities just as natural as the effects known from classical physics. A consequence of this expectation of elegance is:

- **Unity.** It would, frankly, be quite disappointing if the new theory explained, say, only the wave–particle duality while non-locality was merely assumed to be there and the measurement problem was relegated to yet another revolution. Rather, one resolution should naturally entail the others.
- **Continuity.** Scientific revolutions, unlike all too many political revolutions, do not destroy the fruits of earlier theories but rather incorporate them within a new context. This is true not only for the empirical data which the earlier theories revealed, but also for many of their insights and principles, which find their place within the new framework. The new revolution will therefore incorporate not only present-day quantum formalism, but many features of its prevailing interpretations as well.[1]
- **Sacrifice.** All the above cannot come without a price. If the solution to the quantum puzzles has lingered so long, it is most likely being hindered by some highly cherished assumption which no one is willing to give up. We therefore have to prepare for a serious blow that the new theory will inflict on our world view. At this point, proponents of some of the existing interpretations might argue: "But we have already done that! We gave up the notion of objective reality and/or locality!" Well, they did, but unfortunately they did not get much in return. A genuine revolution is balanced differently: For what it has robbed us, it generously rewards us with:
- **Novel Predictions.** While the new theory will no doubt point out where we have been blind all along, as Wheeler so incisively put it, it will not stop there, but go on to tell us what is *out there* that we should now see. In other words, it will make new predictions, challenging us to verify or refute them by experiment or observation. Moreover, the theory will also yield:
- **Unexpected Dividends.** One of the most profound features of reality is that simplicity goes hand in hand with universality. One may drop a basic assumption or even an axiom and, lo and behold, the edifice built on the remaining narrower foundation turns out to be *wider*: additional phenomena, beyond those which one sought to explain, turn out to fit neatly within the new theory. Maxwell's unification of electricity and magnetism, which surprisingly turned out to account for light too, is a prominent example. Similarly, the new explanation of quantum phenomena is almost

[1] For this idea I am indebted to S. Dolev, whom I once observed analyzing a quantum-mechanical experiment in terms of a certain interpretation which I knew he was not partial to. To my inquiry he told me it has been his habit to analyze a complex quantum process in terms of several competing interpretations, as each interpretation illuminates another facet of it. See also Chap. 5 by Hartle.

> bound to illuminate some other conundrum, be it the origin of the universe [9], the nature of consciousness [10], or even something we are as yet unable to conceive of.

Having said all that, it becomes soberingly clear why none of the interpretations of quantum mechanics has won general acceptance in the physical community. To be sure, physics would be very dull had these interpretations not been proposed in the first place. They teased researchers' minds and stimulated experimentation and theorizing. Yet interpretations of quantum mechanics – especially the most ingenious ones – might sometimes do a disservice to their proponents. They might give the impression that quantum mechanics is the final word, and because they are not theories in themselves, offering no predictions that differ from quantum theory proper, they are irrefutable. This is bound to inflict barren tranquility on an over-enthusiastic adherent. Popper's [11] legacy is very instrumental in this context, and can be best appreciated when considering certain pseudo-sciences. Astrology, for example, boasts enormous explanatory power and yet, being irrefutable, is a conceptual ghost: It can never die, hence is not a living theory either. It never really *forbids* anything, hence never makes any other possibility *more likely*.

The lesson should not be lost on the quantum physicist. One should be suspicious of a framework that, instead of trying to resolve contradictions, embraces them with the aid of epistemological or methodological maneuvers, no matter how brilliantly. Contradictions have always been the lifeblood of scientific progress, and they compel us to engage upon *ontological* adventures.

Of course, "Good men must not obey laws too well" (R.W. Emerson), and neither should scientists follow too strictly any guidelines in the search for a new theory. In other words, let us remain loose enough to give Nature ample opportunity to surprise us. Einstein openly advocated a certain degree of looseness when he said that a scientist [12]:

> ... must appear to the systematic epistemologist as a type of unscrupulous opportunist: he appears as realist insofar as he seeks to describe a world independent of the acts of perception; as idealist insofar as he looks upon the concepts and theories as the free inventions of the human spirit (not logically derivable from what is empirically given); as positivist insofar as he considers his concepts and theories justified only to the extent to which they furnish a logical representation of relations among sensory experiences. He may even appear as Platonist or Pythagorean insofar as he considers the viewpoint of logical simplicity as an indispensable and effective tool of his research. (p. 684)

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Participating in this volume has been a huge privilege. Perhaps the sentiments of all of us towards the subject of this volume can best be put in the words of

Rabbi Tarfon (*Ethics of the Fathers* 2, 16): "It is not upon you to complete the work, neither are you free to refrain from it."

References

1. A. Einstein, B. Podolsky, and N. Rosen: Can quantum-mechanical description of physical reality be considered complete? Phys. Rev. **47**, 777 (1935)
2. N. Bohr: Can quantum-mechanical description of physical reality be considered complete? Phys. Rev. **48**, 696 (1935)
3. J.A. Wheeler: In: *Complexity, Entropy, and the Physics of Information*, ed. by W.H. Zurek, Addison-Wesley, New York (1990) p. 3
4. D. Greenberger: Book review, Found. Phys. **31**, 557 (2001)
5. J.A. Wheeler and W.H. Zurek (Eds.): *Quantum Theory and Measurement*, Princeton University Press, Princeton (1983)
6. R.P. Feynman, R.B. Leighton, M. Sands: *The Feynman Lectures on Physics*, Vol. 3, Addison-Wesley, Reading (1965)
7. R. Penrose: Singularities and time-asymmetry. In: *General Relativity: An Einstein Centenary Survey*, ed. by S.W. Hawking and W. Israel, Cambridge University Press, Cambridge (1979) p. 581
8. J.S. Bell: On the Einstein–Podolsky–Rosen Paradox, Physics, **1**, 195–780 (1964)
9. A. Guth: *The Inflationary Universe*, Addison-Wesley, Reading, Ma. (1997)
10. R. Penrose: *Shadows of the Mind*, Oxford University Press, Oxford (1994)
11. K.R. Popper: *Conjectures and Refutations*, Harper, New York (1963)
12. A. Einstein: Reply to Criticisms. In: *Albert Einstein: Philosopher–Scientist*, ed. by P.A. Schlipp, Open Court, La Salle, Ill. (1949)