QUANTUM THEORY AT THE CROSSROADS

The 1927 Solvay conference was perhaps the most important meeting in the history of quantum theory. Contrary to popular belief, the interpretation of quantum theory was not settled at this conference, and no consensus was reached. Instead, a range of sharply conflicting views were presented and extensively discussed, including de Broglie's pilot-wave theory, Born and Heisenberg's quantum mechanics, and Schrödinger's wave mechanics. Today, there is no longer an established or dominant interpretation of quantum theory, so it is important to re-evaluate the historical sources and keep the interpretation debate open.

This book contains a complete translation of the original proceedings, with background essays on the three main interpretations of quantum theory presented at the conference, and an extensive analysis of the lectures and discussions in the light of current research in the foundations of quantum theory. The proceedings contain much unexpected material, including extensive discussions of de Broglie's pilot-wave theory (which de Broglie presented for a many-body system), and a theory of 'quantum mechanics' apparently lacking in wave function collapse or fundamental time evolution. This book will be of interest to graduate students and researchers in physics and in the history and philosophy of quantum theory.

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QUANTUM THEORY AT THE CROSSROADS

Reconsidering the 1927 Solvay Conference

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To the memory of James T. Cushing

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Preface

> And they said one to another: Go to, let us build us a tower, whose top may reach unto heaven; and let us make us a name. And the Lord said: Go to, let us go down, and there confound their language, that they may not understand one another's speech.
>
> *(Genesis 11: 3–7)*

Anyone who has taken part in a debate on the interpretation of quantum theory will recognise how fitting is the above quotation from the book of Genesis, according to which the builders of the Tower of Babel found that they could no longer understand one another's speech. For when it comes to the interpretation of quantum theory, even the most clear-thinking and capable physicists are often unable to understand each other.

This state of affairs dates back to the genesis of quantum theory itself. In October 1927, during the 'general discussion' that took place in Brussels at the end of the fifth Solvay conference, Paul Ehrenfest wrote the above lines on the blackboard. As Langevin later remarked, the Solvay meeting in 1927 was the conference where 'the confusion of ideas reached its peak'.

Ehrenfest's perceptive gesture captured the essence of a situation that has persisted for three-quarters of a century. According to widespread historical folklore, the deep differences of opinion among the leading physicists of the day led to intense debates, which were satisfactorily resolved by Bohr and Heisenberg around the time of the 1927 Solvay meeting. But in fact, at the end of 1927, a significant number of the main participants (in particular de Broglie, Einstein and Schrödinger) remained unconvinced, and the deep differences of opinion were never really resolved.

The interpretation of quantum theory seems as highly controversial today as it was in 1927. There has also been criticism – on the part of historians as well as physicists – of the tactics used by Bohr and others to propagate their views in the late 1920s, and a realisation that alternative ideas may have been dismissed or unfairly disparaged. For many physicists, a sense of unease lingers over the whole subject. Might it be that things are not as clear-cut as Bohr and Heisenberg would have us believe? Might it be that their opponents had something important to say after all? Because today there is no longer an established interpretation of quantum mechanics, we feel it is important to go back to the sources and re-evaluate them.

In this spirit, we offer the reader a return to a time just before the Copenhagen interpretation was widely accepted, when the best physicists of the day gathered to discuss a range of views, concerning many topics of interest today (measurement, determinism, non-locality, subjectivity, interference and so on), and when three distinct theories – de Broglie's pilot-wave theory, Born and Heisenberg's quantum mechanics and Schrödinger's wave mechanics – were presented and discussed on an equal footing.

*

Since the 1930s, and especially since the Second World War, it has been common to dismiss questions about the interpretation of quantum theory as 'metaphysical' or 'just philosophical'. It will be clear from the lively and wide-ranging discussions of 1927 that at that time, for the most distinguished physicists of the day, the issues were decidedly *physical*: Is the electron a point particle with a continuous trajectory (de Broglie), or a wave packet (Schrödinger), or neither (Born and Heisenberg)? Do quantum outcomes occur when nature makes a choice (Dirac), or when an observer decides to record them (Heisenberg)? Is the non-locality of quantum theory compatible with relativity (Einstein)? Can a theory with trajectories account for the recoil of a single photon on a mirror (Kramers, de Broglie)? Is indeterminism a fundamental limitation, or merely the outcome of coarse-graining over something deeper and deterministic (Lorentz)?

After 1927, the Copenhagen interpretation became firmly established. Rival views were marginalised, in particular those represented by de Broglie, Schrödinger and Einstein, even though these scientists were responsible for many of the major developments in quantum physics itself. (This marginalisation is apparent in most historical accounts written throughout the twentieth century.) From the very beginning, however, there were some notes of caution: for example, when Bohr's landmark paper of 1928 (the English version of his famous Como lecture) was published in *Nature*, an editorial preface expressed dissatisfaction with the 'somewhat vague statistical description' and ended with the hope that this would not be the 'last word on the subject'. And there were a few outstanding alarm bells, in particular the famous paper by Einstein, Podolsky and Rosen in 1935, and the important papers by Schrödinger (in the same year) on the cat paradox and on entanglement. But on the whole, the questioning ceased in all but a few corners. A general opinion arose that the questions had been essentially settled, and that a satisfactory point of view had been arrived at, principally through the work of Bohr and Heisenberg. For subsequent generations of physicists, 'shut up and calculate' emerged as the working rule among the vast majority.

Despite this atmosphere, the questioning never completely died out, and some very significant work was published, for example by Bohm in 1952, Everett in 1957 and Bell in 1964 and 1966. But attitudes changed very slowly. Younger physicists were strongly discouraged from pursuing such questions. Those who persisted generally had difficult careers, and much of the careful thinking about quantum foundations was relegated to departments of philosophy.

Nevertheless, the closing decade of the twentieth century saw a resurgence of interest in the foundations of quantum theory. At the time of writing, a range of alternatives (such as hidden variables, many worlds, collapse models, among others) are being actively pursued, and the Copenhagen interpretation can no longer claim to be the dominant or 'orthodox' interpretation.

The modern reader familiar with current debates and positions in quantum foundations will recognise many of the standard points of view in the discussions reproduced here, although expressed with a remarkable concision and clarity. This provides a welcome contrast with the generally poor level of debate today: as the distinguished cosmologist Dennis Sciama was fond of pointing out, when it comes to the interpretation of quantum theory 'the standard of argument suddenly drops to zero'. We hope that the publication of this book will contribute to a revival of sharp and informed debate about the meaning of quantum theory.

*

Remarkably, the proceedings of the fifth Solvay conference have not received the attention they deserve, neither from physicists nor from historians, and the literature contains numerous major misunderstandings about what took place there.

The fifth Solvay conference is usually remembered for the clash that took place between Einstein and Bohr over the uncertainty relations. It is remarkable, then, to find that not a word of these discussions appears in the published proceedings. It is known that Einstein and Bohr engaged in vigorous informal discussions, but in the formal debates recorded in the proceedings they were relatively silent. Bohr did contribute to the general discussion, but this material was not published. Instead, at Bohr's request, it was replaced by a translation of the German version of his Como lecture, which appeared in *Naturwissenschaften* in 1928. (We do not reproduce this well-known paper here.) The appending of this translation to the published proceedings may be the cause of the common misunderstanding that Bohr gave a report at the conference: in fact, he did not.

Born and Heisenberg present a number of unfamiliar viewpoints concerning, among other things, the nature of the wave function and the role of time and of probability in quantum theory. Particularly surprising is the seeming absence of a collapse postulate in their formulation, and the apparently phenomenological (or effective) status of the time-dependent Schrödinger equation. Born and Heisenberg's 'quantum mechanics' seems remarkably different from quantum mechanics (in the Dirac–von Neumann formulation) as we know it today.

De Broglie's pilot-wave theory was the subject of extensive and varied discussions. This is rather startling in view of the claim – in Max Jammer's classic historical study *The Philosophy of Quantum Mechanics* – that de Broglie's theory 'was hardly discussed at all' and that 'the only serious reaction came from Pauli' (Jammer 1974, pp. 110–11). Jammer's view is typical even today. But in the published proceedings, at the end of de Broglie's report there are 9 pages of discussion devoted to de Broglie's theory; and of the 42 pages of general discussion, 15 contain discussion of de Broglie's theory, with serious reactions and comments coming not only from Pauli but also from Born, Brillouin, Einstein, Kramers, Lorentz, Schrödinger and others. Even the well-known exchange between Pauli and de Broglie has been widely misunderstood.

Finally, another surprise is that in his report de Broglie proposed the many-body pilot-wave dynamics for a system of particles, with the total configuration guided by a wave in configuration space, and not just (as is generally believed) the one-body theory in 3-space. De Broglie's theory is essentially the same as that developed by Bohm in 1952, the only difference being that de Broglie's dynamics (like the form of pilot-wave theory popularised by Bell) is formulated in terms of velocity rather than acceleration.

*

This work is a translation of and commentary on the proceedings of the fifth Solvay conference of 1927, which were published in French in 1928 under the title *Électrons et Photons*.

We have not attempted to give an exhaustive historical analysis of the fifth Solvay conference. Rather, our main aims have been to present the material in a manner accessible to the general physicist, and to situate the proceedings in the context of current research in quantum foundations. We hope that the book will contribute to stimulating and reviving serious debate about quantum foundations in the wider physics community, and that making the proceedings available in English will encourage historians and philosophers to reconsider their significance.

Part I begins with a historical introduction and provides essays on the three main theories presented at the conference (pilot-wave theory, quantum mechanics, wave mechanics). The lectures and discussions that took place at the fifth Solvay conference contain an extensive range of material that is relevant to current research in the foundations of quantum theory. In Part II, after a brief review of the status of quantum foundations today, we summarise what seem to us to be the highlights of the conference, from the point of view of current debates about the meaning of quantum theory. Part III of the book consists of translations of the reports, of the discussions following them, and of the general discussion. Wherever possible, the original (in particular English or German) texts have been used. We have tacitly corrected minor mistakes in punctuation and spelling, and we have uniformised the style of equations, references and footnotes. (Unless otherwise specified, all translations of quotations are ours.)

Part I (except for Chapter 2), the reports by Compton, by Born and Heisenberg and by Schrödinger, and the Appendix to Part III are principally the work of Guido Bacciagaluppi. Chapter 2, all of Part II, the reports by Bragg and by de Broglie, and the general discussion in Part III are principally the work of Antony Valentini.

Chapters 2, 10 and 11 are based on a seminar, ‘The early history of Louis de Broglie’s pilot-wave dynamics’, given by Antony Valentini at the University of Notre Dame in September 1997, at a conference in honour of the sixtieth birthday of the late James T. Cushing.

*

To James T. Cushing, physicist, philosopher, historian and gentleman, we both owe a special and heartfelt thanks. It was he who brought us together on this project, and to him we are indebted for his encouragement and, above all, his example. This book is dedicated to his memory.

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Antony Valentini began studying these fascinating proceedings while holding a postdoctoral position at the University of Rome 'La Sapienza' (1994–6), and is grateful to Marcello Cini, Bruno Bertotti and Dennis Sciama for their support and encouragement during that period. For support in recent years, he is grateful to Perimeter Institute, and wishes to express a special thanks to Howard Burton, Lucien Hardy and Lee Smolin.

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Frontmatter
More information

Abbreviations

AEA: Albert Einstein Archives, Jewish National and University Library, Hebrew University of Jerusalem.
AHQP: Archive for the History of Quantum Physics.
AHQP-BSC: Bohr Scientific Correspondence, microfilmed from the Niels Bohr Arkiv, Copenhagen.
AHQP-BMSS: Bohr Scientific Manuscripts, microfilmed from the Niels Bohr Arkiv, Copenhagen.
AHQP-EHR: Ehrenfest collection, microfilmed from the Rijksmuseum voor de Geschiedenis van de Natuurwetenschappen en van de Geneeskunde 'Museum Boerhaave', Leiden.
AHQP-LTZ: Lorentz collection, microfilmed from the Algemeen Rijksarchief, Den Haag (now in the Noord-Hollands Archief, Haarlem).
AHQP-RDN: Richardson Collection, microfilmed from the Harry Ransom Humanities Research Center, University of Texas at Austin.
AHQP-OHI: Oral history interview transcripts.
IIPCS: Archives of the Instituts Internationaux de Physique et de Chimie Solvay, Université Libre de Bruxelles.
Ann. d. Phys. or *Ann. der Phys.*: Annalen der Physik.
Bayr. Akad. d. Wiss. Math. phys. Kl.: Sitzungsberichte der Mathematisch-Physikalischen Klasse der Königlich-Bayerischen Akademie der Wissenschaften (München).
Berl. Ber.: Sitzungsberichte der Preussischen Akademie der Wissenschaften (Berlin).
Acad. Roy. Belg. or *Bull. Ac. R. Belg.* or *Bull. Ac. roy. de Belgique* or *Bull. Ac. roy. Belgique* or *Bull. Ac. roy. Belg.* or *Bull. Ac. R. Belg., Cl. des Sciences*: Bulletin de l'Académie Royale des Sciences, des Lettres et des Beaux-arts de Belgique. Classe des Sciences.
Bull. Natl. Res. Coun.: Bulletin of the National Research Council (U.S.).

Comm. Fenn.: Commentationes Physico-mathematicae, Societas Scientiarum Fennica.
C. R. or *C. R. Acad. Sc.* or *Comptes Rendus Acad. Sci. Paris*: Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences (Paris).
Gött. Nachr.: Nachrichten der Akademie der Wissenschaften in Göttingen. II., Mathematisch-Physikalische Klasse.
J. de Phys. or *Jour. de Phys.* or *Journ. Physique* or *Journ. d. Phys.*: Journal de Physique (until 1919), then Journal de Physique et le Radium.
Jour. Frank. Inst.: Journal of the Franklin Institute.
Lincei Rend.: Rendiconti Lincei.
Manchester Memoirs: Manchester Literary and Philosophical Society, Memoirs and Proceedings.
Math. Ann. or *Mathem. Ann.*: Mathematische Annalen.
Naturw. or *Naturwiss.* or *Naturwissensch.* or *Naturwissenschaften*: Die Naturwissenschaften.
Nat. Acad. Sci. Proc. or *Proc. Nat. Acad. Sci.* or *Proc. Nat. Acad.*: Proceedings of the National Academy of Sciences (U.S.).
Phil. Mag.: Philosophical Magazine.
Phil. Trans. or *Phil. Trans. Roy. Soc.*: Philosophical Transactions of the Royal Society of London.
Phys. Rev.: Physical Review.
Phys. Zeits. or *Phys. Zeitsch.* or *Physik. Zts.*: Physikalische Zeitschrift.
Proc. Camb. Phil. Soc. or *Proc. Cambr. Phil. Soc.* or *Proc. Cambridge Phil. Soc.*: Proceedings of the Cambridge Philosophical Society.
Proc. Phys. Soc.: Proceedings of the Physical Society of London.
Proc. Roy. Soc. or *Roy. Soc. Proc.*: Proceedings of the Royal Society of London.
Upsala Univ. Årsskr.: Uppsala Universitets Årsskrift.
Z. f. Phys. or *Zts. f. Phys.* or *Zeit. f. Phys.* or *Zeits. f. Phys.* or *Zeitsch. f. Phys.* or *Zeitschr. f. Phys.*: Zeitschrift für Physik.

Typographic conventions

The following conventions have been used.

Square brackets [ ] denote editorial amendments or (in the translations) original wordings; [?] denotes an uncertain reading.

Curly brackets { } denote additions (in original typescripts or manuscripts).

Angular brackets < > denote deletions (in original typescripts or manuscripts).

Note on the bibliography and the index

The references cited in Parts I and II, and in the endnotes and editorial footnotes to Part III, are listed in our bibliography. The references cited in the original Solvay volume are found in the translation of the proceedings in Part III.

In the index, under entries for the conference participants, italic page numbers indicate spoken contributions.

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