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The Creation of Quantum Mechanics and the Bohr-Pauli Dialogue

JOHN HENDRY

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STUDIES IN THE HISTORY OF MODERN SCIENCE

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To Dee

PREFACE

Many books have been written on the history of quantum mechanics. So far as I am aware, however, this is the first to incorporate the results of the large amount of detailed scholarly research completed by professional historians of physics over the past fifteen years. It is also, I believe, the first since Max Jammer's pioneering study of fifteen years ago to attempt a genuine 'history' as opposed to a mere technical report or popular or semi-popular account. My aims in making this attempt have been to satisfy the needs of historians of science and, more especially, to promote a serious interest in the history of science among physicists and physics students. Since the creation of quantum mechanics was inevitably a technical process conducted through the medium of technical language it has been impossible to avoid the introduction of a large amount of such language. Some acquaintance with quantum mechanics, corresponding to that obtained through an undergraduate physics course, has accordingly been assumed. I have tried to ensure, however, that such an acquaintance should be sufficient as well as necessary, and even someone with only the most basic grounding in physics should be able with judicious skipping, to get through the book. The technical details are essential to the dialogue, but the plot proceeds and can, I hope, be understood on a non-technical level.

The research for this book has extended over a number of years, and although the bulk of it is published here for the first time some aspects have appeared in my Ph.D. thesis and in a number of published papers. In the course of my work I have received assistance of varying kinds from many teachers and colleagues, and I should like to offer my thanks to them and also to those other colleagues on whose published research I have drawn. The latter, very considerable, debt is recorded in the bibliography. In the former class I should like to mention particularly Gerald Whitrow and Jon Dorling, who oversaw my doctoral research, and David Cassidy, John Heilbron, Erwin Hiebert, Karl von Meyenn and B. L. van der Waerden, who have provided much-needed criticism and valuable encouragement since. I should also like to thank all owners of copyright for permission to reproduce private correspondence, the Royal Society and the British Academy for invaluable financial assistance, and the staff of the old History of Science and Technology

Department at Imperial College, London, of the Niels Bohr Institutet, Copenhagen, and of the Historisches Institut, University of Stuttgart, for hospitality at various times.

Spring 1983 JOHN HENDRY

SCIENTIFIC NOTATION

In most cases, scientific symbols used are defined upon their first appearance. Exceptions are standard notations and the symbols for quantum numbers in the old quantum atomic theory, which are given below.

Standard Notations

c	Speed of light
ν	Frequency
e	Electron charge
m	Particle mass
h	Planck's constant

Quantum Numbers (for alkali atoms with single valence electron)

n	Radial quantum number
l, $k - \frac{1}{2}$, $K - \frac{1}{2}$	Azimuthal quantum number (orbital angular momentum of valence electron)
$j, J - \frac{1}{2}$	Inner quantum number (total angular momentum)
s, R, r	Spin, or angular momentum of atom minus valence electron
m	Magnetic quantum number (total angular momentum in direction of applied magnetic field)

Every sentence I utter is to be understood as a question and not as an affirmative.

NIELS BOHR

In my youth I believed myself to be a revolutionary; now I see that I was a classicist.

WOLFGANG PAULI

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CHAPTER 1

INTRODUCTION

Quantum mechanics has evolved considerably since it first received a definitive formulation and interpretation in 1927. The quantum theory of fields grew up quickly over the next few years and after the discovery of a new range of elementary particles in the 1930s the formulation of field and particle theories has developed apace since the war. But in all this, two things have remained more or less unchanged. On one hand the quantum theory has continued in all its formulations to show a remarkable predictive power in respect of experimental observations. In this respect it must rank as an extraordinarily successful physical theory, and as one that will not easily be displaced. On the other hand, however, dissatisfaction with the conceptual foundations of the theory has also apparently endured. Many working physicists are seemingly content to accept what Einstein referred to as the "gentle pillow" of the Copenhagen interpretation without asking any further questions, and this has long been accepted as an orthodox position. But if we restrict our attention to physicists (or indeed philosophers) of the first rank, then we see immediately that such an orthodoxy is illusory. It was created in the late 1920s when many of the leading quantum physicists, among them Bohr, Born, Heisenberg, Pauli, Dirac, Jordan and von Neumann, sunk their more philosophical differences in an effort to repel the challenge of the semi-classical interpretations and get on with the job of developing quantum electrodynamics. But those differences remained. Copenhagenism was and is a generic term covering a whole range of related interpretations.

Even when these interpretations are taken together, they cannot be considered as an entirely dominant orthodoxy. Among their early opponents some physicists might arguably be dismissed as narrow-sighted conservatives. But such outright dismissal is very difficult to uphold in Einstein's case, and still more so in those of Schrödinger and de Broglie, neither of whose preferred interpretations could reasonably be labelled classical. More recently attention has shifted from the physical interpretation of quantum mechanics towards the logical and mathematical consistency of quantum field theory, but the issues remain closely connected and opposition to Copenhagenism remains strong. However, and here lies the crux of the matter, the opponents seem to be no nearer to providing a valid alternative than were their predecessors of the late 1920s. Beyond the limited compromise of Copenhagenism there is still no such thing as a consistent and generally acceptable interpretation of quantum mechanics, and the evidence of the last fifty years points unerringly to the conclusion that there will not be one until either the structure of our physical conceptions, or our expectations of physical theory, or the quantum theory itself should undergo radical changes more far-reaching than any yet seen.

Faced with this dilemma it is tempting to react as did Peter Debye to the problem of electrons in the nucleus, a problem that arose in the immediate wake of quantum mechanics, by treating it as something best ignored, "like the new taxes". And many physicists have indeed taken this course, either ignoring the interpretative problem altogether (paying the taxes without question) or proceeding stubbornly to seek fundamentally classical interpretations that are demonstrably not there (stalling the taxman). But whereas such attitudes may be expedient in the short term they are ultimately inconsistent with the very spirit of the scientific enterprise. Wolfgang Pauli, who will turn out to be one of the main actors in the story that follows, responded to Debye's suggestion by announcing publicly his hitherto private speculations on the existence of the neutrino. He was convinced that any positive line of exploration was better than none at all, and this conviction quickly bore fruit as the existence of the neutrino was confirmed. The interpretative problem of quantum theory is several orders more fundamental than that of nuclear electrons, and has proved immensely more resistant to attempts at a solution. But a theory with innate inconsistencies, whatever its present predictive success, cannot be expected to serve for ever. If the problem, like the tax, does not bear thinking about, then that is the strongest indication we can possibly have that it needs thinking about. And while it may not be so easily solved we can at least try to understand how such an extreme situation arose in the first place.

One aim of this study, then, is to approach the history of the theory of quantum mechanics as a means of exploring its philosophy. We shall not address ourselves explicitly to the various attempts to impose philosophical positions upon the completed theory. But by looking at the conceptual features surrounding its genesis, and at the philosophical and other preconceptions built into its structure and foundations, we shall try to come to a clearer understanding of these attempts, of the chronic differences of opinion they reflect, and of the essential nature of the problem they address.

The second aim is to present the history of quantum mechanics in such a way as to enable it to be related to the mainstream of intellectual history, not through the study of surface parallels reflecting the prevailing themata of the milieu, but through that of the essential conceptual changes underlying these.

With these aims in mind, the history will necessarily be a selective one, and the selection may sometimes appear arbitrary. The concentration will be upon the course of matrix mechanics, for example, at the expense of that of wave mechanics. This is not to deny the historical importance of the latter theory, but it is the former, the work of an interacting group rather than of a succession of individuals, in which the conceptual tensions can most easily be seen. Again, though the listed contents of the history will inevitably have much in common with those of the existing accounts, the emphasis will be very different. In particular there will be no attempt made to give anything like a complete account of the more technical developments within quantum theory, which have been well treated elsewhere and are covered by the bibliography. The same holds also for the prevailing philosophical milieu, so long as its notions were not applied directly and consequentially to physical problems. Instead the concern here will be with the middle area, with fundamental but specific epistemological and methodological beliefs, and with the manifestation of these beliefs both in the general debate on the quantum problems and, especially, in the major technical advances.

Straightforward as it is, this perspective requires some comment, for the concern of historians to date has tended to be with either the technical development of quantum mechanics or its conceptual background, as expressed through largely undefined philosophical debates, such as that on the causality issue. Even where the two aspects have been treated by the same historian, as by Paul Forman in his wide range of scholarly papers, they have remained imperfectly connected. But whatever the immediate concern of the historian it is this very connection that is most crucial to the dynamics of the events being considered.

The language of modern theoretical physics is that of symbolic models and mathematical equations, and although a physicist may think in terms of physical or metaphysical concepts he must continually translate his thoughts into this working language. It provides not only the means of communication within the physics community but also those between the underlying principles of physics on one hand and the highly artificial experimental results on the other. It is thus an omnipresent and irreducible part of the development of physical science. And, this being the case, the innovations of the 1920s were inevitably of a highly technical, symbolic and mathematical nature. Any attempt to reduce them completely to abstract conceptual developments automatically distorts the historical process and introduces a gulf between story and evidence that is historically unacceptable. But in seeking to understand why as opposed to how the innovations took place, and in seeking to extract the true essence of these innovations, it is the development of abstract concepts that is of the most relevance and interest. This poses a problem for the historian. The physicists concerned with a particular set of problems did not all share the same influences and concerns; each one approached the current issues, both technical and philosophical, from a different conceptual framework. Some no doubt did see the technical problems of quantum theory as just that, and others no doubt saw the historically elevated causality issue as the most fundamental imaginable. But this was patently not the case for the most innovative of the quantum physicists, who derived their views on both subjects from more fundamental concerns.

It is usually impossible to connect a scientist's deepest, usually religious, concerns with his scientific work, and no attempt will be made to do this here. But it is possible to relate both the technical development of quantum mechanics and the surrounding philosophical debate to more fundamental issues concerning the concepts used to describe the physical world. The aim here will therefore be to trace the development of these issues, and of their manifestation in the evolution of quantum mechanics. This done it should be possible to place the interpretative problem of quantum mechanics in a somewhat clearer historical light than hitherto, to relate the interpretations offered more closely and accurately to currents of thought prevailing in other fields, and even to get a clear idea of what type of interpretative problems remain.

The plan of the study is to begin with an analysis of the conceptual background to quantum mechanics in terms both of the commonly perceived issues (causality, energy conservation, the wave-particle duality) and of the fundamental epistemological and methodological problems manifest at about the same time in the context of general relativity theory and the search for a unified field theory. Having shown how these latter problems were carried over into the quantum context we shall then relate the conceptual background first to the technical problems encountered in the old quantum theory, then to the genesis and reception of the ill-fated virtual oscillator theory, and then to the genesis in 1925 of Heisenberg's "new kinematics", the foundation stone of quantum mechanics. Through this first part of the study the evolving theme will be one of a debate, its origins in the quest for a unified general relativistic field theory, between the established master, Niels Bohr, and the up-and-coming Wolfgang Pauli. And in the second part we shall take this theme as a guide through the evolution of quantum mechanics, from Heisenberg's breakthrough to the establishment of a definitive formulation and interpretation in 1927. We shall look first at the early exploration of the meaning, significance and implications of the new kinematics, then at the early evolution of wave mechanics and at the attempts of Heisenberg, Pauli and Dirac to integrate the technical advances of this theory with the fundamental concepts of Heisenberg's. A predominant theme in this part of the story will be an ongoing attempt to base quantum mechanics upon a foundational framework consistent with these characteristic concepts; and in the ensuing sections we shall show how this attempt, building upon the insights achieved in the wake of wave mechanics, led first to the definitive formalism of the statistical transformation theory in Hilbert space, and then to Heisenberg's uncertainty principle. All these developments took place largely within the framework of Pauli's ideas, but in the last section of the main story we shall turn back to the other side of the fundamental debate and trace the evolution of Bohr's principle of complementarity and the compromise of the Copenhagen group of interpretations.

The characteristic of quantum mechanics that made it a truly revolutionary theory of physics was its explicit rejection of the classical criterion of a consistent visualisation of physical events. For centuries natural philosophers had argued whether a consistent picture in space and time was the ideal to which all theories should aspire or an idol imposed by the tyranny of the senses, the worship of which could only stand in the way of truth. By the time the issue was put to the test in the context of the quantum paradoxes, however, the old debate had apparently been long forgotten, and it was not immediately obvious just what was at stake. The role of visualisation was subsumed under more general questions as to the operational foundations of physical concepts, and indeed remained so subsumed throughout the creation of the theory. Throughout our study too, then, the central theme will be that of the status and applicability of physical concepts. As we reach the end of the story, this theme will merge into that of *Anschaulichkeit*, sometimes translatable as visualisability, sometimes as something less specific to the visual sense. Broadly speaking the path will be from the competing demands of visualisation on one hand and physical operationalism on the other towards a common recognition that neither ideal was obtainable.

CHAPTER 2

WOLFGANG PAULI AND THE SEARCH FOR A UNIFIED THEORY

INTRODUCTION: MANIFESTATIONS OF DUALITY

It has been customary for historians investigating the background to quantum mechanics to concentrate on one or other of the particular branches of quantum physics. In some cases this approach may be vindicated by a similar specialisation on the part of physicists whose work is being discussed. But even though they may have published only within restricted areas, most physicists took their perception of the problem complex from the wider field of their reading, correspondence and conversation. And most of those involved in the actual development of quantum mechanics had already contributed important work in several distinct areas. In general, the major conceptual issues ran through all such areas, and their most obvious and widely discussed manifestations were not necessarily their most significant. The wave-particle duality, which was almost certainly the most characteristic conceptual feature of quantum theory, was most commonly discussed in the contexts of experimental X-ray physics and individual absorption and emission phenomena. This discussion reached its peak, in the years immediately before the development of the new quantum mechanics, in the context of the Compton effect, viewed by at least one historian as a turning point in physics.[1] But by the time of Compton's experiments this whole area had long been one of only secondary importance for the active development of ideas pertaining to the duality problem, and dramatic though his results were to a wider audience they had relatively little impact on the physicists whose work was to be of importance in the creation of quantum mechanics.[2]

Ever since the turn of the century, and especially since the demonstration of X-ray diffraction in 1912, discrete X-ray phenomena had offered the clearest and best-known demonstration of the localised particulate properties of light, just as the continuous absorption of interference phenomena provided the clearest portrayal of its non-localised wave-like nature. But following the work of Poincaré, Ehrenfest and Jeans it was clearly recognised by about 1913 that any proof of this dual nature of light rested not on the individual wave and particle phenomena but on the statistical behaviour of black-body