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Introduction

The philosophical problems posed by quantum mechanics were evident to many of the founders of the theory from its inception in the mid-1920s. More than 80 years later, many of these issues continue to generate much debate and disagreement. Yet we are only just beginning to understand the history of the interpretations of quantum mechanics, through the careful study of the work of leading physicists who figured prominently in the classic debates of the 1930s. According to the standard view found in much of the secondary literature, the discussions between Niels Bohr and Werner Heisenberg in Copenhagen in the first half of 1927 laid the foundations for what is commonly referred to today as the 'Copenhagen interpretation of quantum mechanics'. At the 1927 Como and Solvay conferences Bohr presented his concept of complementarity, which in his view provided a new conceptual framework for understanding quantum mechanics. This view, which Bohr would develop further in the late 1920s and 1930s, is frequently understood to be the philosophical foundation of the Copenhagen interpretation of quantum mechanics, which called for a dramatic revision of the hitherto accepted foundations of physics and epistemology. As Dugald Murdoch explains, 'By the end of 1927 the Copenhagen interpretation had established itself as the dominant interpretation of quantum mechanics' (Murdoch, 1994, p. 303). While there were dissenting voices, notably those of Einstein, Schrödinger and Planck in the 1930s, it is widely recognised that Bohr's views prevailed in the decades that followed and became the basis of the 'orthodox view'.

But precisely what the Copenhagen interpretation is, or what it tells us about the world of atoms and electrons, turns out to be a rather difficult question to answer. As Susanne Gieser points out, 'Many attempts have been made to characterize and analyse the philosophical and epistemological position of the Copenhagen School and especially of Bohr, and its significance in the emergence of the definitive interpretation of quantum mechanics' (Gieser, 2005, p. 56). Indeed, despite an extensive literature which discusses and criticises the so-called

'Copenhagen interpretation', and the philosophical position which underpins it, there remains no agreement on what it is. The lack of clarity about precisely what constitutes the Copenhagen interpretation stems partly from the fact that none of the founding fathers of quantum mechanics ever set out in a clear fashion the basic tenets of the orthodox interpretation. Indeed, while Bohr's concept of complementarity was hailed by many of his contemporaries as 'the most significant result for philosophy that crystallized out of modern physics' (Jordan, 1944, p. 131; see also Pauli, 1980, p. 7; 1994), Bohr's writings were interpreted through a variety of different philosophical perspectives ranging from logical positivism (Jordan, 1936, p. vii; Frank, 1957, pp. 216–17; 1975, pp. 162–5) and neo-Kantianism (Weizsäcker, 1971a, 1994) to dialectical materialism (Rosenfeld, 1979a) and subjective idealism (Blokhintzev, 1952). Moreover, von Neumann, Dirac and Wigner – all of whom made significant contributions to the development of the orthodox interpretation of quantum mechanics – either completely ignored or were explicitly critical of Bohr's notion of complementarity (Bub, 1995). As Max Jammer points out in his *Philosophy of Quantum Mechanics*,

> the Copenhagen interpretation is not a single, clear-cut, unambiguously defined set of ideas but rather a common denominator for a variety of related viewpoints. Nor is it necessarily linked with a specific philosophical or ideological position. It can be, and has been, professed by adherents to most diverging philosophical views, ranging from strict subjectivism and pure idealism through neo-Kantianism, critical realism, to positivism and dialectical materialism.
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> *(Jammer, 1974, p. 87)*

In a similar vein, Erhard Scheibe warns us 'that there is no point in looking for *the* Copenhagen interpretation as a unified and consistent logical structure' (Scheibe, 1973, p. 9). The term 'Copenhagen interpretation', Scheibe argues, refers to the divergent, and sometimes conflicting, views of physicists 'who played an important role in the establishment of quantum mechanics, and who were collaborators of Bohr's at his Institute or took part in discussions during the crucial years'. This view has more recently found support in the works of John Hendry (1984, p. 1), Catherine Chevalley (1999, pp. 173, 189), Mara Beller (1999, pp. 9, 173) and Don Howard (2004). As each of these authors suggests, beneath the veneer of agreement one finds hidden discord and debate between the various adherents of the so-called 'Copenhagen interpretation'. In order to arrive at a deeper understanding of the history of interpretations of quantum mechanics we must look beyond the supposed 'unity of the Copenhagen school' and focus on the views of the individual physicists.

This book contributes to just this task, by examining the philosophical interpretation of quantum mechanics of one of the most important physicists

of the Copenhagen school – Werner Heisenberg (1901–76). Born in Würzburg, Heisenberg studied the new quantum theory in Munich under Arnold Sommerfeld in the early 1920s. In the winter of 1922–3 he spent time in Göttingen as Max Born's assistant before gaining his *venia legendi* at Göttingen University. He also spent several months at the Institute for Theoretical Physics in Copenhagen in 1924–5 and again in 1926–7, where he collaborated closely with Bohr. During this period, Heisenberg produced two of his most important works – his seminal paper on matrix mechanics, which he published in July 1925, and his celebrated paper on the uncertainty principle, published in March 1927. Heisenberg was among the brightest young stars in a new generation of theoretical physicists, who were instrumental in the creation of quantum mechanics in the 1920s. In recognition of his contribution, he was awarded the Nobel Prize in physics in 1932. By the age of 26 Heisenberg had secured a full professorial appointment as a lecturer in Theoretical Physics at Leipzig University. He would go on to become one of the pioneers of quantum electrodynamics and quantum field theory in the 1930s, and make important contributions to the field of nuclear physics before turning his attention to the search for a unified field theory of elementary particles in the 1950s (Hermann, 1977; Kleint & Wiemers, 1993). Heisenberg's impact on theoretical physics in the twentieth century was the subject of two symposia in 2001 in commemoration of the centenary of his birth (Papenfuβ, Lüst & Schleich, 2002; Buschhorn & Wess, 2004).

Heisenberg is remembered today as one of the principal architects of quantum mechanics, but he was also one of its most insightful interpreters. He brought an unusually profound grasp of the philosophical problems involved, matched only in depth and significance by Bohr. Heisenberg devoted considerable attention to the philosophical foundations of quantum mechanics and wrote extensively on that subject. However, his writings on the epistemological and ontological questions, which underpinned his interpretation of quantum mechanics, have received only scant attention and remain the source of considerable misunderstanding and ambiguity. This work attempts to address this lacuna in Heisenberg scholarship and the history of the interpretations of quantum mechanics.

1.1 Heisenberg's philosophy of quantum mechanics

To speak of Heisenberg's philosophy of quantum mechanics is somewhat misleading. Heisenberg's philosophical viewpoint did not remain fixed throughout his lifetime, but underwent significant transformation in the late

1920s and 1930s. In focusing on the way in which Heisenberg's thought evolved over time, this book brings to light a number of the key themes that emerged in his writings between 1925 and 1960. Here the historical development of Heisenberg's thought can be properly understood only by situating it in the context of his discussions with other physicists such as Bohr and Einstein, as well as his contact with various philosophical schools of thought in the German-speaking world, all of which left their mark on his thought. While I think that a deeper appreciation of Heisenberg's thought offers something of value to those interested in the philosophy of quantum mechanics, the task of the present work should be understood primarily as historical, rather than as a contribution to contemporary debates in the philosophy of physics. Indeed, Heisenberg left a number of key issues unresolved or ambiguous in his later writings. To this extent, my aim in writing this book has not been to defend Heisenberg's philosophical position, but merely to understand it.

In attempting to piece together a coherent picture of the development of Heisenberg's philosophy of quantum mechanics, this work draws on two different historiographical approaches. The first is the 'dialogical historiography' outlined by Mara Beller and John Hendry, which seeks to emphasise 'the complex dialogical nature of thought' in the history of science (Beller, 1999, p. 3). In his biography of Heisenberg, David Cassidy suggests that he depended on conversations with 'his friends and colleagues for philosophical stimulus' (Cassidy, 1992, p. 48). Taking up this approach, one finds that his philosophy of quantum mechanics was shaped not by private meditation on the problems posed by the new theory, but rather by his dialogues, encounters and correspondence with other physicists and philosophers of his time, primarily with Bohr but also with Einstein, Schrödinger, Pauli and Weizsäcker. The second approach is taken from the work of Catherine Chevalley, who has argued that we cannot fully understand the original interpretations of quantum mechanics without appreciating the precise philosophical context in which they developed. She declares that '*history of science* and *history of philosophy* are equally necessary' (Chevalley, 1994, p. 50, emphasis in original). In taking this perspective I examine the historical development of Heisenberg's thought by situating it against the background of the divergent reactions to Kant's philosophy in the German-speaking world in the 1920s and early 1930s. Only through an integration of the history of science and the history of philosophy, mediated by discussions with his contemporaries, can we more adequately grasp and appreciate the manner in which Heisenberg's philosophy of quantum mechanics took shape over time.

This work is divided into three parts. Each of these corresponds roughly to a historical phase in the development of Heisenberg's thought, though there is

considerable overlap between them. Part I of this work deals with Heisenberg's philosophical viewpoint which arose during the *emergence* of quantum mechanics in the period between 1925 and 1927. In particular, this section is devoted to shedding light on two principal themes explained in Chapters 2 and 3: the observability principle, which is widely thought to have inspired his ground-breaking 1925 paper on quantum mechanics; and the subsequent clash between Heisenberg and Schrödinger in 1926–7 over what it means to *understand* a physical theory, which underpinned the different attitudes to the problem of interpretation in matrix mechanics and wave mechanics.

Part II of the book deals with a number of themes which emerge in the context of *Heisenberg's dialogue with Bohr* in the period between 1926 and 1930 concerning the interpretation of quantum mechanics. Chapters 4, 5 and 6 examine three key ideas that arose in discussions with Bohr during this critical period: (i) the notion of the wave–particle duality; (ii) the concept of indeterminacy and the limited applicability of classical concepts; and (iii) Bohr's viewpoint of complementarity. In each of these chapters I have attempted to trace not only the ways in which Heisenberg's thinking on these issues owed a debt to Bohr, but also how his point of view marks a departure from Bohr's. Part III focuses on the final phase in the development of Heisenberg's *epistemology* and *ontology* of quantum mechanics. By the mid-1930s Heisenberg had begun to view the problem of reality in quantum mechanics as inextricably linked to a reformulation of Kant's notion of the *a priori* and the world-disclosing function of human language.

What emerges from this study of the historical development of Heisenberg's philosophy is a complex but decisive shift from a broadly empiricist outlook to a philosophical viewpoint which embraces the constitutive dimension of human language. The earlier phase of Heisenberg's thought bears the influence of Einstein's theory of relativity, or, to be more precise, the strongly positivistic tendency which many of Heisenberg's contemporaries, Einstein included, considered integral to the theory. This is evident in three ways: first, in his introduction of the principle of observability into quantum mechanics in 1925; secondly, in an instrumentalist view of understanding in physics and the subsequent redefinition of *Anschaulichkeit* (visualisability); and thirdly, in an operational analysis of kinematic concepts in 1927. In each of these cases, Heisenberg attempted to draw an explicit or implicit analogy with the philosophical lessons of the theory of relativity, or, to put it more precisely, the positivistic attitude which he felt had underpinned the Einsteinian conception of space and time. However, as I argue in Chapter 3, Heisenberg's instrumentalism requires more careful attention. Although he described the task of physics to uncover empirically adequate mathematical laws, he also took the view that

once a theory had reached the status of a 'closed theory' in physics – through an axiomatic structure which described a wide range of empirical phenomena – as quantum mechanics had by 1927, one could interpret the theory as in some way representing the form or structure of reality itself and not merely as a phenomenological description. In this sense Heisenberg's philosophical view was in some way closer to 'structural realism' than to instrumentalism.

We can see the beginnings of the shift away from positivism in Heisenberg's thought in his discussions with Einstein and Bohr in 1926–7. Here Heisenberg recognised the problematic nature of the concept of observability (discussed in Chapter 2) and the operational point of view (discussed in Chapter 5). The abandonment of operationalism, which had played an important role in his analysis of the gamma-ray microscope thought experiment in the 1927 paper on the uncertainty relations, in particular, marked an important turning point in Heisenberg's thought. After discussions with Bohr, Heisenberg arrived at the view that it was not possible, as he had previously thought, to replace classical concepts like position and momentum with new quantum concepts in the description of experimental phenomena. By the 1930s, influenced by discussions with his student and friend Carl Friedrich von Weizsäcker and the visiting Kantian scholar Grete Herman, Heisenberg began to stress the importance of Kant's philosophy for understanding quantum mechanics. Yet Heisenberg was no orthodox Kantian. As I show in Chapter 7, his later epistemology is characterised by a transformation of Kant's notion of the *a priori*. The classical forms of intuition of space and time are for us the conditions for the possibility of all experience, but at the same time they have only limited applicability. Moreover, such forms do not, for Heisenberg, originate in 'pure reason' but emerge historically through our interplay with the world. In this sense, space and time prove to be indispensable as conditions for the possibility of empirical science, and yet they are not transcendental in Kant's strict sense.

By the 1940s the positivism characteristic of his early approach had been abandoned in favour of a different epistemological view in which the world-disclosing function of language assumes central importance. Here we find that Heisenberg situates the paradoxes of quantum mechanics within what I have termed a 'quasi-transcendental', as opposed to an analytic, conception of language. As Heisenberg would put it, somewhat paradoxically, 'for us there is only the world in which the expression "there is" has meaning'. The beginnings of this philosophical attitude can be traced back to his critical exchanges with Bohr in Copenhagen in 1927, which centred on the indispensability of classical concepts. Here Heisenberg came to the realisation that while quantum mechanics demanded an abandonment of the classical analytic concept of motion, certain forms of classical thought such as space and time were

indispensable for a description of experience, even in quantum mechanics. Rather than replacing the concepts of classical physics with new quantum concepts, or with operational definitions, Heisenberg now resigned himself to the fact that we cannot dispense with the concepts of classical physics, in spite of their limitations. Here Heisenberg would depart from his earlier emphasis on the elimination of unobservables and an operational definition of concepts, recognising that 'we are suspended in language'. By the 1950s one can discern in Heisenberg's philosophy his own 'linguistic turn' according to which 'objective reality' has meaning for us only within the framework of space and time. Somewhat paradoxically then, the quantum world cannot be deemed 'objectively real', but is merely a world of 'possibilities' or 'potentialities'.

Notwithstanding Bohr's immense influence on Heisenberg, the latter's epistemology remained distinct from those of his Danish colleague on several critical points. While scholars such as Beller and Howard have emphasised the point that Bohr and Heisenberg disagreed in important ways, little attention has been devoted to disentangling their respective views of wave–particle duality and complementarity (Beller, 1999, p. 9). This is precisely the task of Chapters 4 and 6. Heisenberg's understanding of the wave–particle duality is based on the formal *symmetry* or *equivalence* of wave and particle descriptions, not the necessity of using them in mutually exclusive experimental arrangements in Bohr's sense. Indeed, while Heisenberg often presented himself as an enthusiastic proponent of Bohr's concept complementarity, his view of the complementarity of space-time and causal description is based on a misunderstanding of a crucial passage in Bohr's Como lecture. Indeed, whereas Bohr emphasised that mutually exclusive experimental arrangements serve to define the conditions for the *unambiguous* use of classical concepts such as position and momentum, Heisenberg was inclined to see this situation as highlighting the inherent *ambiguity* in the use of classical concepts in the complementarity description. Drawing on a careful textual analysis of Bohr's and Heisenberg's writings, as well as recent scholarship which has clarified certain aspects of Bohr's notion of complementarity, we can see more clearly the hidden, but nonetheless, substantial differences in their respective philosophical positions on the interpretation of quantum mechanics and the defence of the 'completeness' of quantum mechanics in the 1930s. Such divergences have gone largely unnoticed, as they were often buried within Heisenberg's carefully worded exposition of these ideas.

It is important, however, not to overstate the divergences between Heisenberg and Bohr. Mara Beller, in her important book *Quantum Dialogue*, argues that Heisenberg only ever paid lip service to Bohr's doctrine of the indispensability of classical concepts, but that he did not subscribe to this view consistently

(Beller, 1999, pp. 182, 197–9). However, in my view, Beller's conclusion is based on a misunderstanding of the crucial passages in which Heisenberg articulated his position. The accusations of inconsistency frequently levelled at Heisenberg, while sometimes warranted, are in this case based on a failure to subject his writings to careful scrutiny. While on several occasions Heisenberg drew a contrast between the ambiguity of our everyday language and the precision of the mathematical description in physics, after 1930 he never deviated from the view that when asked to describe the *results* of our measurements 'we are forced to use the language of classical physics, simply because we have no other language in which to express the results' (Heisenberg, 1971, pp. 129–30). A close reading of the relevant texts shows that by the late 1920s Heisenberg became convinced that classical concepts were indispensable for a description of experience in quantum mechanics, though his reasons for holding this view, and the epistemological viewpoint which eventually underpinned it, differed from Bohr's.

1.2 Heisenberg as a philosopher-physicist

In the words of Don Howard, 'The fifty years from 1880 to 1930 was the era of the philosopher-physicist' (Howard, in press). Here Howard identifies Einstein as the leading figure in 'a whole generation of scientists' including Bohr, Heisenberg, Pauli, Schrödinger and Weyl, all of whom could be 'equally well described as philosopher-physicists'. Yet the image of Bohr as the philosophical leader of the Copenhagen school has meant that Heisenberg has remained largely in Bohr's shadow. In 1965, Patrick Heelan declared, 'the epistemology of quantum mechanics has up to now been studied almost exclusively through the works of Bohr', whereas 'Heisenberg's philosophy has been curiously untouched' (Heelan, 1965, pp. ix–x). Heelan's *Quantum Mechanics and Objectivity: A Study of the Physical Philosophy of Werner Heisenberg*, which was published in 1965, remains to my knowledge the only major study published in English of Heisenberg's philosophy of physics. By contrast, the last 30 years have witnessed a continuation of scholarly interest in Bohr's philosophy of quantum mechanics in the English-speaking world, much of which has attempted to locate Bohr's views in the framework of the realism debate in the philosophy of science (Folse, 1985; Honner, 1987; Murdoch, 1987; Faye, 1991; Favrholdt, 1992; Faye & Folse, 1994).

As one might expect, Heisenberg's philosophy has attracted more attention from scholars in continental Europe than in the Anglophone world, as is evident in Herbert Hörz's *Werner Heisenberg und die Philosophie* (1968) and Guiseppe

Gembillo's *Werner Heisenberg: la filosofia di un fisico* (1987). More recently the proceedings of two conferences held in 1991 and 2001 devoted to Heisenberg's physics and philosophy have been published (Geyer, Herwig & Rechenberg, 1993; Gembillo & Altavilla, 2002). While these works offer some valuable insights into Heisenberg's philosophy of physics, they remain virtually unknown in the English-speaking world. There has, however, been a new surge of interest in Heisenberg's philosophy of physics over the last decade or so, particularly concerning his notion of the 'closed theories' in physics. The recent work of scholars like Alisa Bokulich (2006) and Melanie Frappier (2004) has done much to re-examine some of the key ideas in Heisenberg's philosophical thought. Beyond this the works of Catherine Chevalley (1988), Carl Friedrich von Weizsäcker (1971b, 1987) and Jan Lacki (2002), though by no means constituting systematic studies of Heisenberg's interpretation of quantum mechanics, provide useful insights into some of the central themes in Heisenberg's philosophy of physics.

It is important to note that this book differs from the major studies undertaken by Heelan, Hörz and Gembillo, both in approach and in scope. Heelan frames his reading of Heisenberg largely in terms of Husserl's transcendental phenomenology. Though he quotes extensively from Heisenberg's writings, Heelan's primary aim is to give his own philosophical interpretation of quantum mechanics, rather than engaging in serious historical scholarship. In attempting to trace the development of Heisenberg's thought, Heelan argues that after 'an early and predominantly empiricist phase', Heisenberg 'passed to a predominantly rationalist viewpoint … inspired almost totally by the transcendental philosophy of Kant' (Heelan, 1965, pp. xiii–xiv). While Heelan quite rightly recognises that Heisenberg moved away from an early empiricist phase, he fails to appreciate the different forms this empiricism assumed in Heisenberg's early work, and his subsequent critique of the observability principle and the operational standpoint in the late 1920s. Moreover, his claim that Heisenberg's later thought is best described as a 'rationalist viewpoint' is somewhat problematic. Neo-Kantian philosophy certainly exerted an important influence on Heisenberg, but his later writings are explicitly critical of the rationalist viewpoint espoused by Kant, and embrace a far more pragmatic outlook largely influenced by Bohr and Weizsäcker. Indeed, in a letter to Pauli in 1935, Heisenberg commented that he found the dissertation by the neo-Kantian scholar Grete Hermann to be 'reasonable', though perhaps too much inclined to 'the rationalist philosophical tendency' (Heisenberg to Pauli, 2 July 1935, Pauli, 1985, p. 408 [item 414]). Heisenberg saw quantum mechanics as having brought about a pragmatic revision of Kant's notion of *a priori* knowledge – a theme which I elaborate on in Chapter 7.

While useful in drawing attention to the otherwise neglected aspects of Heisenberg's thought, the books of Hörz and Gembillo pay little attention to the historical development of Heisenberg's interpretation of quantum mechanics, preferring to focus on his relationship with the various philosophical traditions with which he came into contact. Furthermore, these works do not limit themselves to an investigation of the philosophy of quantum mechanics but examine Heisenberg's later philosophy on the unified field theory of elementary particles, which increasingly drew him towards some kind of neo-Platonism (Hörz, 1968, pp. 220–68; Sallee, 1983; Gembillo, 1987, pp. 1–65). By contrast, this work does not address the search for a unified field theory, which constituted the central task of Heisenberg's physics after 1950, but confines itself solely to Heisenberg's philosophical understanding of quantum mechanics. To this extent this book can only be but a first step in exploring Heisenberg's overall worldview. A comprehensive account of Heisenberg's philosophical vision would require a more detailed examination of his later neo-Platonism, his enigmatic notion of the 'central order', as well as his views on the relationship between science, culture and religion.[1] A comparison of the scientific and religious worldviews of Heisenberg and Planck is to be found in the recent work of Cornelia Liesenfeld (1992) and Wilifred Schröder (1999).

Despite Heisenberg's extensive writings on epistemological questions, there has been a tendency to portray Heisenberg as having contributed little of significance or originality to the philosophy of quantum mechanics. In his biography, David Cassidy argues that as a physicist Heisenberg exercised only 'a modest, usual interest' in philosophy (Cassidy, 1992, p. 255). This view finds some support from Weizsäcker, who portrays Heisenberg as someone who saw himself first and foremost as a physicist, not a philosopher, and to this extent remained somewhat reluctant to immerse himself in the epistemological problems of modern physics (Weizsäcker, 1985, p. 184). When Heisenberg did turn his attention to philosophy, 'his interest … was primarily neither ontological nor epistemological but one of an aesthetic nature' (Weizsäcker, 1987, p. 287). Yet at the same time Weizsäcker acknowledges that 'Heisenberg's was a philosophical mind'. Indeed, Heisenberg had hoped to co-author a book with Weizsäcker on the 'philosophical relevance of modern physics', through an examination of different schools of thought such as materialism, positivism, Thomism, critical idealism, Hegelianism and Platonism (Weizsäcker, 1971b, p. 11). Though the book was never written, Heisenberg's published writings give the distinct impression of a thinker preoccupied with the philosophical implications of

[1] Gregor Schiemann from the University of Wuppertal has recently completed a book on Heisenberg's philosophy which focuses on some of these themes (Schiemann, 2008).