Chapter 1
Introduction and Outline

Abstract The scientific development of elementary Quantum Theory will be described, relying on original publications of the major contributors and letters during the same period of time. Recollections from later times are omitted intentionally. Years or decades past have the inevitable tendency to blur and often embellish the glorious past; it is attempted to avoid these effects. The main emphasis will be on physical concepts and ideas; mathematical formulae will be kept to a strict minimum, essential for the understanding. It will be stressed that mathematical representations are interchangeable, the physical content may be described in many different ways.

Keywords Planck's radiation law · Planck's quantization hypothesis · Einstein's light quanta · "Old Quantum Theory" · Matrix mechanics · Wave mechanics · "Measurement problem" · Uncertainty relations · Complementarity principle · Copenhagen interpretation · Space-time continuum

Quantum Theory emerged from the endeavor to understand the spectral distribution of radiation in thermal equilibrium with matter. Max Planck's discovery of the radiation law introduced a new universal constant, the quantum of action, marking the start to the "quantum age". The next revolutionary step was taken by Einstein, who recognized that light is constituted of elementary objects, light quanta, having particle properties. During the following years atomic and molecular spectroscopy became the major experimental technique to obtain further insight into the behavior on atomic scales. Nevertheless, the vast literature on the historical development of elementary Quantum Theory—written by practicing scientists, historians, and philosophers of science—typically deals with Quantum Mechanics alone; quantization of radiation is assumed to have played no role.

The central elements of the orthodox accounts may be condensed briefly into the following: The path to a valid Quantum Mechanics in 1925/26 is argued to start from the old Bohr-Sommerfeld Quantum Theory of 1913–1924, which rejected Einstein's light quanta; radiation was believed to retain classical properties. A decisive breakthrough—attributed to Heisenberg's paper of July 1925—is seen to provide the basis for a calculational scheme, matrix mechanics. Schrödinger's wave mechanics, which followed almost instantly, is seen as an independent achievement.

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The recognition of the equivalence of matrix mechanics and wave mechanics then follows. The next milestone is attributed to Heisenberg's uncertainty relations, which are claimed to arise from unavoidable disturbances caused by any measurement of physical variables, leading to the notorious "measurement problem". Bohr's Complementarity principle, attributing dual properties—both wave and particle-like—to photons, electrons, and other particles, completes the so-called Copenhagen interpretation of Quantum Mechanics. The orthodox view is summed up in Max Jammer's book, published in 1966, "The Conceptual Development of Quantum Mechanics":

> "...the conceptual situation as brought about by the establishment of the so-called Copenhagen interpretation ..... is de fact the only existing fully articulated consistent scheme of conceptions that brings into order an otherwise chaotic cluster of facts and makes it comprehensible".

This view will be challenged in the following. It will be shown that Einstein's contributions between 1905 and 1924 provided the basis for Max Born's radically new physical concepts, which relied on Einstein's elementary Quantum Optics to define a path towards Quantum Mechanics. In 1905 Einstein introduced the photon; radiation is quantized, consisting of particles with energies and momenta. In 1917 Einstein's paper "On the Quantum Theory of Radiation" contains the necessary conditions for thermal equilibrium between radiation and matter. Einstein's Quantum Optics provided the starting point for Max Born towards a valid Quantum Theory, combining Quantum Mechanics and Quantum Optics. Born concluded that quantization of action required truly discontinuous behavior of all phenomena in nature; the quantal behavior of matter and radiation are mutually dependent, only their combination may provide a consistent theory. All transitions require the action variables to change by integer values of Planck's quantum of action h. Atomic systems can no longer be described by position and time variables varying continuously, but by quantum numbers; discontinuous transitions between different states are describable only by probabilities. The space-time continuum has lost its meaning on elementary scales: In order to define a precise point in space or a precise instant of time, we can only rely on the objects, which nature provides; these objects themselves are subject to quantum laws. A definite point in a space-time continuum looses its meaning on atomic scales, because we need atoms or electrons for their definition; but atoms and electrons themselves do not have precise space-time variables. This understanding led to the Quantum theory of Max Born, Werner Heisenberg, and Pascual Jordan in 1925.

The role of Heisenberg was ambiguous as an intermediate between Göttingen, where he was Born's Assistent, and Copenhagen, where he collaborated with Bohr. Already in 1925 he was primarily influenced by Bohr's thinking and ideas, less by Born's more radical physical concepts. Substantial differences in concepts and understanding remained between Born-Jordan on one side and Bohr-Heisenberg on the other.

This book will proceed as follows:

The scientific development of elementary Quantum Theory will be described, relying on original publications of the major contributors and letters during the same period of time. Recollections from later times are omitted intentionally. Years or decades past have the inevitable tendency to blur and often embellish the glorious past; it is attempted to avoid these effects. The main emphasis will be on physical concepts and ideas; mathematical formulae will be kept to a strict minimum, essential for the understanding. It will be stressed that mathematical representations are interchangeable, the physical content may be described in many different ways.

The very brief Chap. 2 stresses the fundamental differences between continuous and deterministic classical physics to discontinuous and statistical quantum properties.

Chapter 3 starts with a brief account of the path leading to Planck's introduction of the quantum of action. Extensive discussions of Einstein's contributions between 1905 and 1924 follow; they demonstrate the mutual dependence of quantization of radiation and matter. The introduction of the photon in 1905 is extended to include the application of quantization to the properties of matter in 1907. Of decisive importance is Einstein's Quantum Theory of radiation of 1917, which will serve as starting base for the future matrix mechanics. Further milestones are Einstein's application of Bose statistics to particles in 1924, the recognition of quantum theoretical indistinguishability, and the predictions of Bose-Einstein condensation and interference-like phenomena for particles with finite mass.

Chapter 4 provides a brief description of the central elements of the Bohr-Sommerfeld "Old Quantum Theory".

Chapter 5 contains the background and the essential publications for the development of matrix mechanics from 1919 to 1925. The path leads from Born's suggestion in 1919 that the space-time continuum looses its meaning on the quantum scale to the implementation of discontinuous quantum transitions ("*Quantensprünge*") in 1924, when the term "Quantum Mechanics" ("*Quantenmechanik*") is introduced. In June 1925 Born and Jordan introduce discontinuous "quantum vectors" ("*Quantenvektoren*")—which will later become "matrix elements"—to combine Einstein's elementary Quantum Optics with Born's "Quantenmechanik". Heisenberg's "reinterpretation paper" ("*Umdeutung*") of 1925 introduces matrix multiplication rules for the "quantum vectors", which are used by Born and Jordan in September 1925 to achieve the final breakthrough: Commutation relations and quantum equations of motion. The "three men's paper" ("*Dreimännerarbeit*") of Born, Heisenberg, Jordan of November 1925 completes the formal development of matrix mechanics.

Chapter 6 contains continuous representations of the new quantum laws. Kornel Lanczos pointed out this possibility, used by Max Born and Norbert Wiener to represent "time" by a continuous variable again. Schrödinger's wave mechanics—representing position as continuous variable—provided a mathematic method more familiar than the unusual algebra. Schrödinger conceived it as rejection of the radically new concepts; he refused to give up the space-time continuum: "*Das räumlich-zeitliche Denken*" (i.e. the mode of thought relying on continuity in space and time) should remain the only acceptable way to conceive of processes in nature and remain to be the basis for the understanding of the laws of nature.

Chapter 7 discusses the consequences of the basic quantum laws on "wave-like" phenomena and quantum uncertainties. The uncertainty relations are generally attributed to Heisenberg. Heisenberg's justification, however, based on necessary disturbances introduced by the measuring process, will turn out to be erroneous. Bohr's "Complementarity principle", postulating "particle-wave duality", completes the so-called Copenhagen interpretation of Quantum Mechanics. Particle-wave duality will be shown to be a mathematical artifact without physical significance.

Chapter 8 describes the decided opposition of Einstein and Schrödinger to the Copenhagen interpretation. Einstein's understanding of Quantum Theory is described in detail based on his own writings. According to Einstein the **"EPR paper"** (Einstein, Podolsky, Rosen, 1935) was written by Podolsky and does not properly contain Einstein's own stance.

Chapter 9 contains discussions of orthodox accounts of the development of Quantum Mechanics. The classical books by Max Jammer (1966) and B. L. van der Waerden (1967) represent the Copenhagen point of view; the multi-volume work of Jagdish Mehra and Helmut Rechenberg (1982) is similar in general conclusion. The essential differences to the conclusions reached in the present account are illustrated.

Chapter 10 describes later opposition to the Copenhagen interpretation. The logical consistency of the Copenhagen interpretation—in particular Bohr's "philosophical" pronouncements—are viewed with growing skepticism by historians and philosophers of science.

The appendix on elementary scattering processes demonstrates the physical content of the fundamental equations of Quantum Theory. The inconsistencies in Heisenberg's and Bohr's arguments become apparent. Disturbance-free measurements are not only possible, but are used routinely in diffraction phenomena, which measure not only average particle positions but their respective quantum uncertainties as well. Particle-wave duality is shown to be neither necessary nor helpful.

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