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The Conceptual and the Anecdotal History of Quantum Mechanics

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The aim of this paper is to combine the intellectual and the psychosocial aspects, blurring the distinction between the conceptual and the anecdotal history of quantum mechanics. The full realization of the importance of such "anecdotal" factors leads to the revision of our understanding of the conceptual development itself. The paper concludes with the suggestion that a major part of numerous inconsistencies in the Copenhagen interpretation of quantum physics are of a psychosocial origin.

Professor Max Jammer's pioneering classic is entitled *The Conceptual Development of Quantum Mechanics* (Jammer, 1966). Sometimes the comprehensive description and the penetrating analysis of pivotal events in this book is interrupted by historical "anecdotes," which disclose the emotional, or "irrational," side of the founders of quantum theory. These "anecdotes" are no more than diversions—they play no essential part in the evolution of the conceptual story itself. Professor Jammer clarified his methodological position on the very first pages of his book: "... even the strict chronological order of presenting the material has often been violated in favor of the logical coherence of the discussion" (Jammer, 1966, VII).

The aim of this paper is to integrate the conceptual and the anecdotal history. As Einstein once remarked: "It is not the brain which controls human beings but the spinal cord—the seat of instincts and blind passions. Even scientists are no exception to this." The annals of science provide an overwhelming support for this judgment.

Historians and sociologists of science have recorded many cases of bitter controversies and frantic races for priority—fierce competition that is invariably accompanied by intense emotions.

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Nor is this phenomenon absent in the history of quantum physics. Intense confrontations occurred between Einstein and Stark, Dirac and Fermi, Born and Bethe, and Heisenberg and Schrödinger. Sociologists of science, from the very beginning of the emergence of their discipline, have recognized the effect of such emotions on the rate of scientific progress, on the local and the national scale. They have also discussed the negative role of emotions for the development of science, since emotions supposedly distort rational reasoning and cause behavior that deviates from the established social norm (Merton, 1957). Recent historiography of science attributed to psychological and social factors a more substantial formative role. The very distinction between the "internal" and the "external," between the "cognitive" and the "psychosocial," is increasingly questioned.

In this paper I will argue that the "psychosocial" factors shaped the intellectual efforts and determined the cognitive choices in the development of the quantum theory and its interpretation. I do not claim that we can substitute "psychosocial categories" for the "cognitive" ones, that we can always reduce "reasons" to "motives." Yet, without taking the "motives" into account, we often get a distorted picture of what the "reasons" were. The quantum revolution which occurred between 1925–1927 cannot be fully understood if we remain only in the cognitive domain.

As I have mentioned, there are two histories of quantum mechanics—the conceptual one and the anecdotal one. The anecdotal history comprises the fascinating folklore about heated passions, wounded egos, and "human confusion" (Pauli's characterization). I would like to offer one connected story, to merge the "conceptual" and the "anecdotal" into a unified account. By taking emotions seriously, as a heuristic pointer, we will obtain a different conceptual story of the quantum revolution from the one usually presented.

The subjects that I will deal with in this paper—Heisenberg's uncertainty principle and Bohr's complementarity—were analyzed extensively in many excellent historical studies, from Jammer's pioneering works (Jammer 1966, 1974) till recent valuable contributions (Darrigol, 1992). Yet most of these studies concentrate on the conceptual development, shunning out the social, psychological, emotional, and "irrational." I will cover this well studied territory from the psychosocial perspective.

The foundations of the new quantum mechanics were laid in the summer of 1925 in a most remarkable paper by Werner Heisenberg (Heisenberg, 1925). Heisenberg's paper is a fascinating example of those truly innovative works which represent the fusion, or tension, between the old and the new, and which later are incorrectly perceived as a total break with the past. Heisenberg's paper was very radical, almost indigestible, in its appearance, very revolutionary in its consequences, but conservative and ingeniously cautious in its procedure. Continuity with the past was ensured by what was called at the time "the sharpened use" of Bohr's correspondence principle. The sharp formulation of this principle established not only that quantum and classical formulas must coincide in the macroscopic limit, but also that in the microdomain the basic structural connection between the electronic motion and the properties of the emitted radiation must be of the same form (Jammer, 1966; Darrigol, 1992). In order to preserve this connection and to introduce into the theory's foundations the observed discreteness of spectral lines, Heisenberg replaced the classical kinematical variables by properly reinterpreted quantum mechanical analogues. These turned out to be abstract mathematical symbols, subject to a noncommutative algebra. When Max Born realized that Heisenberg's peculiar algebraic rules were nothing more than familiar matrix algebra, he, together with Jordan and later Heisenberg, elaborated the basic formalism of the new quantum theory. The theory was presented in a highly abstract and axiomatic way, in the typical Göttingen mathematical style, and seemed completely dissociated from Bohr's philosophy and the physicalistic reasoning which initially inspired it. The authors implied, for example, that all the quantum discontinuities must be mathematically deduced rather than a priori postulated. The new matrix mechanics was presented as flowing from the positivistic principle of elimination of hypothetical unobservable entities from physics. In my earlier work I have argued that this principle was not the guiding principle of the new scientific advance, as has usually been assumed, but rather a posteriori justification of the technical method, which de facto eliminated the classical positions and orbits within the atom (Beller, 1985).

I have also argued that the original matrix mechanics was not a particulate theory, for the concept of an intra-atomic particle was severely undermined by Heisenberg's reinterpretation procedure (*ibid.*). Originally the meaning of matrix elements was an electromagnetic one, through their connection with the properties of the emitted radiation (The position matrix, as Heisenberg and Lorentz pointed out, was simply a symbolic artefact, which had initially no connection with a position in regular space). An atom became a black box, the internal workings of which were announced to be unintelligible in principle. One cannot, and should not, it was argued, form any anschauliche (intuitive, visualizable) models of the atom (Miller, 1984; Beller, 1985). This inevitable loss of Anschaulichkeit, the authors stated, was fully compensated by an outstanding technical advance (see, for example, Jordan, 1927a).

Only a few months after these developments, a powerful rival theory appeared, one that did not have the disadvantage of a loss of Anschaulichkeit. Schrödinger's wave theory combined the intuitive and adequately developed mathematical formalism with conventional physical concepts in a familiar space-time. Schrödinger's theory was an instant and dazzling success, not only because of its intuitive appeal and unsurpassed theoretical elegance, but also because it immediately provided the solution of the central problems of the atomic domain. It was enthusiastically welcomed by the entire scientific community. Only the authors of matrix mechanics reacted to Schrodinger's theory with immediate hostility. Heisenberg, as he later revealed, simply hoped that the theory was wrong. Dirac felt that because there was already one version of the new quantum mechanics, no other was needed. After Schrödinger proved that his theory and the matrix theory were equivalent, Heisenberg related to wave mechanics as a convenient mathematical tool for calculation of matrix elements, devoid of any physical meaning (Beller, 1992b).

Schrödinger reacted emotionally to this hostility, and also changed his attitude to matrix mechanics. In his first communication (Schrödinger, 1926a), he emphasized the common tendencies of the two theories (both theories undermined the concept of the intra-atomic orbits). He also stated there that both approaches would complement rather than compete with each other. Yet only a few months later, Schrödinger argued passionately that his theory was not only not inferior, but actually superior to the matrix version, and that the highly abstract formalism of matrix mechanics, which operated with such formal notions as transition probabilities, was not conducive to the further progress of physics (Schrödinger, 1926b). Schrödinger also embarked on a series of attempts to interpret the phenomena in the microdomain by exclusively using the continuous wave concepts, such as representing a free particle by a wave packet, and an atom as a superposition of waves which would have beats, or peaks of intensity, with just the correct radiation frequencies. Schrödinger hoped that his approach would eliminate what he considered to be the "irrational quantum jumps." No wonder neither Bohr himself, nor the authors of matrix mechanics, were too sympathetic to Schrödinger's aspirations to relegate Bohr's discontinuous concepts to the status of Ptolemaic epicycles. Matrix physicists rightly perceived Schrödinger's program as a severe threat to their own achievement.

The intense and fascinating confrontation between Schrödinger and Heisenberg resulted in a series of important papers, which focused on two central concepts—*Anschaulichkeit* and discontinuities. In essence, the arguments of an ongoing series of papers could be summarized by stating the two following opposing claims. It is the matrix theory which is a superior theory because it is much more suited than the wave theory to represent the undeniable irreducible discontinuous aspect of quantum phenomena—claimed Heisenberg. It is the wave theory which is superior because it does not suffer from suppression of intuition (*Anschauung*) and allows the solution of concrete scientific problems connected with experiment, argued Schrödinger. Matrix mechanics, claimed Schrödinger in one of his publications, is characterized by a repelling, even horrifying unintuitiveness ("abschrekender, ja abstossender Unanschaulichkeit") (Schrödinger, 1926b). Schrödinger's own work (Schrödinger, 1926b), where he proved the equivalence of both theories, clearly demonstrated that Schrödinger had no problem whatsoever in mastering this abstract formalism (*ibid.*).

Initially, Heisenberg chose to ignore the issue of *Anschaulichkeit*. In a letter to Pauli (on June 8, 1926 in *Pauli's Correspondence*), Heisenberg called Schrödinger's accusations of *Unanschaulichkeit* "*Mist*" (rubbish). In the paper Heisenberg published in June of 1926 (Heisenberg, 1926), he ignored Schrödinger's challenge, simply replying that Schrödinger's wave theory, being a theory in an abstract, multidimensional space, and not in a regular three-dimensional space, is really no more visualizable than his own matrix theory. As late as October 1926, after Born's and Pauli's probability interpretation, Heisenberg wrote in a letter to Pauli (on October 28, 1926, in *Pauli's Correspondence*) that space-time concepts are not applicable to the individual particle, but are perhaps statistical concepts, meaningful only for a large number of particles (similar to the concept of temperature). Yet three months later, in his indeterminacy paper, Heisenberg restored the regular space-time for individual corpuscles. He restored the particulate motion within an atom and even redefined intuition so as to render matrix mechanics visualizable. Matrix mechanics, as opposed to its original nonintuitive interpretation with electromagnetic underpinnings, was transformed by Heisenberg into "intuitive" particulate statistical theory. What is the reason for Heisenberg's about-face?

Towards the winter of 1926, Schrödinger's success, which Born, not without envy, called the "worldwide victory of wave mechanics" was undeniable. An influx of papers, most following Schrödinger's methods and ignoring the matrix one, swelled the scientific literature. This situation annoyed the ambitious Heisenberg very much. He used the word "abscheulich" (repelling) not only about Schrödinger's work, but also about other papers which substantiated the wave theoretical point of view. Thus, Heisenberg found Darwin's and Wentzel's work "abscheulich" (letter to Pauli on March 9, 1927 in *Pauli's Correspondence*). Irritably, Heisenberg complained that physicists should also learn the matrix language (*ibid.*). Realizing the severity of Schrödinger's threat, Heisenberg finally decided to counter Schrödinger on his own terms.

Even though Heisenberg's uncertainty paper (Heisenberg, 1927) is widely known for the elimination of classical causality, the causality issue was merely a peripheral one. It did not appear even in the paper's abstract.

Heisenberg's main concern was to provide a new interpretation of the quantum domain which would render the matrix formalism intuitive, or *anschaulich.*

The paper begins with Heisenberg's definition of what it means to understand a physical theory in an intuitive way: "We believe that we intuitively understand a physical theory when we can think qualitatively about individual experimental consequences and at the same time we know that the application of a theory never contains internal contradictions." By analyzing a number of thought experiments, such as determining the position of an electron by gamma-ray microscope, Heisenberg came to the conclusion that qualitative analysis confirms the quantitative formulas (for example, those which express the uncertainty relations between physical variables). Heisenberg concluded that matrix mechanics should no longer be considered unintuitive: all the classical kinematical concepts can, after all, be retained in the quantum domain, if one gives up their rigorous simultaneous use. In order to dispel any doubt about whose accusations he was refuting, Heisenberg appended a footnote, reminding his readers of Schrödinger's aggravating remark about the "repelling, horrifying nonintuitability" of matrix mechanics. It is not the nonintuitiveness of the matrix mechanics, but the misleading "intuitiveness" of Schrödinger's theory that has hindered the progress of physics, Heisenberg concluded.

Heisenberg was able to provide these ingenious redefinitions by making a complete about-face in his philosophical position. He was reassured in this, as he later recalled, by a remark of Einstein, who objected to the earlier positivistic approach of matrix mechanics by arguing that "it is the theory that decides what we can observe." But if initially Heisenberg had claimed that it is the experimental electromagnetic entities which should determine the new theoretical structure, now he argued that it was the theory which gives meaning to experiment. Consequently, the electron's position ceased to be unobservable and matrix mechanics ceased to be nonintuitive, and was transformed by Heisenberg into a statistical theory of particles in a regular space-time. It is this cognitive reversal that cannot be understood, I believe, on the basis of the conceptual evolution alone.

I would not wish to leave the impression that there were no intellectual reasons for making this cognitive choice. Certain considerations by Schrödinger implied that electronic charge distribution within an atom, or electrons' intra-atomic motion, adequately determines the properties of emitted radiation. (In fact, Born's statistical interpretation of wave function as determining the probability of electronic position was, to a large degree, a translation of Schrödinger's original suggestion into localized particle language.) Dirac's brilliant advances toward generalized transformation theory further incorporated the particulate statistical viewpoint. Yet, as

Heisenberg's correspondence reveals, he restructured his thinking not so much, or at least not only, because new theoretical insights became available, but as a result of his emotional response to the pressure of a non-cognitive kind.

Another emotion of Heisenberg's, which had a crucial impact on his reasoning, was his belief in the finality of his achievement. Belief in the finality of a theory is an emotional choice, or ideological stand, and not a scientific judgment. This belief was premature, for there were conceptual and technical problems yet to be solved. Jordan, for example, did not believe that quantum mechanics was in its final form. He pointed to experimental situations, such as continuous electronic trajectories in the Wilson chamber, which cannot be expressed by the quantum formalism (Jordan, 1927b).

Heisenberg's belief in the finality of matrix mechanics was crucial for the release of an ingenious resolution of the problem. If the theory is final, there can be no situation that cannot be handled by the theory—reasoned Heisenberg. So if there is a discrepancy between the theory and nature, too bad for nature. Perhaps, he daringly thought, we really do not observe a continuous path, but a sequence of discrete and ill-defined spots through which the electron passes. In fact, all we see in a cloud chamber are individual water droplets which are certainly larger than the electron. The right question should therefore be: could we represent the fact that the electron finds itself approximately in a given place and it moves approximately with a given velocity? (Heisenberg, 1971, pp. 77–78). The electronic path, according to Heisenberg's reinterpretation, became a discrete statistical sequence of measured points, subject to uncertainty relations.

We can conclude now that the need to persuade the scientific community of the validity of matrix mechanics and to disseminate this (highly abstract) theory was both a motivation, and an implicit presupposition of Heisenberg's intellectual efforts. Without Schrödinger's challenge of *Anschaulichkeit*, Heisenberg's discovery and formulation of the uncertainty principle would hardly have been possible. My conclusion is that the social, communicative aspect was crucial in the very process of discovery, and not merely in the "marketing" of the "finished" scientific product—the so-called "context of justification."

At times Heisenberg's intense emotions blinded his scientific judgment. A striking example of this kind is related to Heisenberg's clash with Bohr over the uncertainty paper. In describing the γ-ray *gedanken* experiment, Heisenberg committed quite a trivial mistake, which Bohr (and Dirac) were quick to point out. Heisenberg argued that when a photon collides with an electron during a position measurement, the photon transfers to the electron a discrete and uncontrollable amount of momentum. This transfer is the reason for the inevitable uncertainty in the determination of electrons' momentum, or velocity. Even today, this reasoning can be found in some books, but it is, of course, fallacious. One is dealing here with a perfectly deterministic classical situation of two colliding particles, to which conservation laws are applicable, and therefore one cannot deduce the uncertainty. Uncertainty follows not from the uncontrollable electron's recoil, but from the wave-theoretical analysis of the beam of photons, as Bohr pointed out.

That a physicist of Heisenberg's stature could make such a trivial mistake is puzzling enough, but Heisenberg's adamant refusal to correct the mistake, despite Bohr's powerful opposition, is incomprehensible, unless we realize that Heisenberg had some vested interest in preferring a misleading description to the correct one. Heisenberg could not substitute Bohr's description for his own because the whole fabric of Heisenberg's argument against Schrödinger, based exclusively on discontinuity considerations, would collapse by introducing Bohr's continuous wave-theoretical concepts. Years later, Heisenberg admitted that in his uncertainty paper he wanted to avoid wave concepts altogether (Interview with Heisenberg, AHQP). This interpretation is confirmed by the exchange of letters between Heisenberg and Pauli in May 1927 (*Pauli's Correspondence*). Heisenberg expressed once more his view that discontinuity is the most basic and interesting feature of the quantum world. One cannot overemphasize this discontinuity, wrote Heisenberg, and this is the reason, he explained, that he was happy about the paper, despite the mistakes (Heisenberg to Pauli, May 16, 1927, in *Pauli's Correspondence*). Matrix theory was more suited to express discontinuities than Schrödinger's wave mechanics, so Heisenberg found himself "in the battle for the matrices and against waves. ("So bin ich in einen Kampf für die Matrizen and gegen die Wellen gekommen") (Heisenberg to Pauli, May 31, 1927, in *Pauli's Correspondence*). In zealous defense of this camp, ("In Eifer dieses Kampfs") he "overreacted," Heisenberg admitted, to Bohr's correct objections (*ibid.*).

Clearly Heisenberg went to considerable length to secure and defend his own past achievement. Yet the intensely ambitious Heisenberg is not unique in this sense. It is hard to imagine that any scientist would easily take an intellectual stand that would undermine his own achievement. It is quite inconceivable that Bohr and Schrödinger would have reversed their roles after the appearance of Schrödinger's mechanics—such as Bohr advocating the elimination of the discontinuous quantum jumps, while Schrödinger insisting on preserving them. It is not accidental that only a few weeks after the appearance of his first paper on wave mechanics, Schrödinger attempted to construct an interpretation of physical reality using exclusively wave concepts, as it is not accidental that 300 years before him, Descartes, a few months after discovering analytical geometry, decided that perhaps physics was nothing but geometry. The natural tendency to enhance one's own past achievement hardly makes for a disinterested intellectual search.

"Overreacted" is a mild term to describe the extremely tense confrontation between Bohr and Heisenberg. Bohr relentlessly urged Heisenberg to withdraw the uncertainty paper from publication. As Heisenberg recalled, at some point he burst into tears, unable to sustain Bohr's enormous pressure (Interview with Heisenberg, AHQP). Yet Heisenberg did not yield to Bohr. As a result, the relations between them were strained to such a degree that only skillful diplomatic intervention by Oskar Klein and Wolfgang Pauli brought some reconciliation.

Heisenberg's recollections singled out the metaphysical disagreement over the status of wave-particle duality as the major reason for their confrontation. But could mere metaphysical disagreement have produced such a violent clash, or was perhaps Bohr's position more complex than is usually assumed?

Bohr's interpretation of quantum physics was announced by him at the Como Conference in Italy in 1927 (Bohr, 1927), where Bohr presented for the first time his principle of complementarity. The principle of complementarity, according to the usual accounts, dissolved the long standing wave–particle dilemma. Bohr proclaimed that atomic objects do not have well-defined properties, or attributes, which are objectified in the classical way. The atomic attributes are relational, meaningful only in a given experimental context. In certain experiments atomic entities exhibit wave properties, in other experiments—the particulate ones. The consistency is assured by the fact that mutually exclusive experimental arrangements are needed in order to bring out the mutually contradictory attributes. This formulation implies, of course, a far-reaching revision of the classical idea of reality, according to which objects exists and have well-defined properties irrespectively of being observed or not.

While this very brief summary of Bohr's complementarily principle is a fair description of Bohr's later thought (after 1935), it is a far cry, as I have argued (Beller, 1992a), from Bohr's initial elaboration of his philosophy in 1927. Reading Bohr's Como lecture in the usual way does not make much sense—both because it is not clear what the big quarrel between Heisenberg and Bohr was, and because most of Bohr's Como lecture becomes incomprehensible—a complaint that seems to be shared by most students of Bohr's work. I have proposed a different reading of Bohr's Como lecture (Beller, 1992a). This reading not only allows one to decipher a very important scientific text, but also fuses the anecdotal and the conceptual history.

My reinterpretation of Bohr's Como lecture (Beller, 1992a) can be summarized in five main theses:

1. The central message of Bohr's Como lecture is an extensive defense of his idea of stationary states. An important thread running through the whole paper (Bohr, 1927) is his claim of compatibility of the continuous wave mechanics with the discreteness implied by the quantum postulate (the usual accounts single out the wave–particle duality and the uncontrollability of the measurement interaction as Bohr's central claim).

2. Bohr's discussion is asymmetrical in favor of waves (the usual historical accounts perceive Bohr's Como lecture as announcing the symmetrical solution of the wave–particle dilemma).

3. In his Como lecture, Bohr further rejects the idea of photons as point particles (the usual accounts report Bohr's acceptance of the particulate nature of photons as a result of the failure of Bohr–Kramers–Slater theory).

4. Bohr discusses the "harmony" between the wave-theoretical definition and experimental observation (the usual accounts perceive Bohr's Como lecture as announcing the operational definition of concepts).

5. The Como lecture reveals a basic incompatibility between Bohr's and Heisenberg's positions (the usual accounts assume a similarity between their positions, regarding disagreements between Bohr and Heisenberg as minor).

I will briefly discuss points 1, 2, and 5. Bohr never accepted Heisenberg's depreciation of the physical significance of Schrödinger's theory. Bohr himself repeatedly claimed that the decisive importance of wave mechanics, as opposed to the matrix one, lay not only in its unprecedented solving power, but also in its indispensability for the elucidation of the physical meaning of the quantum theory. Bohr's discussion in the Como lecture was based on the idea of a wave packet, very close to Schrödinger's spirit. It is wave packets, rather than point particles, that are used by Bohr all throughout the Como lecture whenever light quanta or electrons are described—both in cases of free particles and in cases of interaction.

Though Bohr's reasoning in the Como lecture is very ingenious, the underlying wave imagery is remarkable simple. The wave-packet idea provides both the tool and the limit of visualizability, or applicability of particulate space-time concepts. Because the stationary state, having a precise energy, is characterized by a single proper vibration, no space-time picture of an atom in a given stationary state can be formed. Or, to quote Bohr: "because every space-time feature is based on consideration of interference inside a group of elementary waves, a consistent application of the concept of stationary state excludes any specification of the behavior of the separate particles in the atom" (Bohr, 1927).

This formulation of complementarily of space-time and energy-momentum for the stationary state has far-reaching consequences. First of all, it implies an irreconcilable gap between Bohr's wave-theoretical and Heisenberg's particulate kinematical positions. As opposed to Heisenberg, Bohr claimed that no statements about kinematics of particles in a given stationary state is possible. In particular, according to Bohr, the usual formulation of the uncertainty principle is inapplicable to the interior of an atom (*ibid.*). Part of the obscurity of the Como lecture lies, in fact, in Bohr's attempt to conceal this gap between his and Heisenberg's position.

Bohr's realization that space-time pictures are excluded by the concept of a stationary state provided him with a crucial retrospective insight into the past failures of the old quantum theory, which mistakenly employed description of stationary states in terms of electrons' continuous space-time orbits. Much of the Como lecture loses its obscurity, when one realizes that its major part is devoted to Bohr's defense of his own idea of stationary state, and to the exploration of the circumstances in which this idea can be consistently employed. The very reason for Bohr's enthusiasm about Schrödinger's wave mechanics was its ability to adequately represent a single stationary state, as opposed to the matrix approach which had no mathematical tools for such a representation (Beller, 1983). This interpretation is confirmed by Bohr's correspondence at the time. Thus, Bohr wrote in a letter to Kronig in 1926: "just in the wave mechanics we possess now the means of picturing a single stationary state. In fact, this is the very reason for the advantage which the wave mechanics exhibits when compared with the matrix method" (quoted in Beller, 1992a).

It is remarkable, though not surprising, to what extent the cognitive positions of Heisenberg and Bohr coincided with their personal-professional interests. Bohr emphasized the wave aspect of matter and radiation: wave ontology allowed him to elucidate and to entrench his conception of a stationary state—Bohr's major contribution to physics. Heisenberg, who had no direct investment in this idea, wanted to avoid waves altogether, in order to argue the superiority of the matrix mechanics to which he contributed so decisively. The emotions, then, are not an aberration—they are the vital fuel for forming cognitive commitments, they are the trigger for the occurrence of breakthroughs.

The priority issue was also not absent from Bohr's confrontation with Heisenberg. For months they struggled in Copenhagen to make sense of the nonsensical quantum world, having desperate and endless discussions. Bohr was not eager to allow Heisenberg to publish the uncertainty paper, letting Heisenberg reap all the fruits from their common struggle. As

Heisenberg put it: "perhaps it was also a battle over who did the whole thing first" (Interview with Heisenberg, AHQP). Passions did indeed run high between Heisenberg and Bohr, yet the metaphysical disagreements were not the only, and perhaps not even the main, issues.

According lo the usual historical accounts, the disagreement between Bohr and Heisenberg ended when Heisenberg "realized" Bohr's point of view and accepted complementarity. But the contemporary correspondence reveals no agreement of this kind, but rather Heisenberg's continuing criticism of Bohr's position. As becomes clear from Heisenberg's letters to Pauli at the time, Heisenberg believed that a contradictory free interpretation should make use of a single coherent system of concepts, and not of two incompatible ones (Heisenberg to Pauli on May 16, 1927, in *Pauli's Correspondence*. Yet there was no public display of disagreement: the illusion was created that there is no essential difference between Bohr's and Heisenberg's position. As Heisenberg later recalled, they soon realized "that all that mattered now was to present facts in such a way that they will be accepted by all physicists" (Heisenberg 1971, p. 79).

Copenhagen–Göttingen physicists presented a united front against the opposition, despite the disagreements among themselves over such basic questions as whether the laws of quantum theory are statistical in principle and applicable only to many particles (as Born and Jordan held), or whether quantum mechanics made meaningful statements about individual phenomena, as Bohr and Heisenberg believed. Often they publicly endorsed the stand of a member of the group, not compatible with their own. This resulted in contradictions which are incomprehensible, unless we take the psychosocial context into account. A particularly striking example is Heisenberg's public endorsement of Bohr's principle of complementarity. As we mentioned, Heisenberg was highly critical of Bohr's view. Heisenberg's belief that the wave language and particle language, being equivalent descriptions of one and the same reality; were mutually convertible and not simultaneously necessary, was soon to be supported by the papers of Jordan and Klein, and Jordan and Wigner, published in 1928 (discussed in Jammer, 1966). These papers proved the equivalence between the wave description and the operator description of particles obeying Fermi statistics. When Kuhn asked Heisenberg why he endorsed Bohr's complementarity nevertheless, Heisenberg replied "Why not? I realized it did not do harm to my interpretation. On the other hand, I never believed it was necessary" (Interview with Heisenberg, AHQP). Heisenberg, in fact, disclosed years later that he never believed in the dualistic description of Nature (*ibid.*). Yet at the time Heisenberg published papers in which he presented his own view, and a few paragraphs later endorsed Bohr's view, incompatible with his own! Such internal contradictions are incomprehensible if we remain in the body of the published work.

Many physicists, historians, and philosophers of science have singled out a remarkable feature of quantum mechanics: while quantum theory is a theory of an unprecedented solving power, equally unprecedented are the disagreements over, and inconsistencies in, its philosophical interpretation. A major source of such inconsistencies is of a sociohistorical origin. It is a meaningful merging of the "conceptual" and the "anecdotal" history that can disclose the context and the source of the numerous contradictions in the Copenhagen interpretation of quantum physics.

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