Schrödinger's and Everett's Interpretations of Quantum Mechanics and Bohr's Experimental Critique

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Abstract:

Upon closer examination, Hugh Everett's compelling account of relative state displays a number of remarkable, fundamental similarities to the ideas proposed by Erwin Schrödinger at the beginning of the quantum revolution in 1926.

In his 1926 papers, Schrödinger argued against Niels Bohr's discontinuous and indeterministic account of quantum phenomena, suggesting that the atomism of classical mechanics fails with regard to very small dimensions of the path and very great curvatures. Ray optics and classical mechanics fail analogously. The true laws of quantum mechanics show that the particle cannot be treated as a single unit, but rather as a manifold of paths. Schrödinger developed the philosophical consequences of such a view in his later writings. Everett similarly started from the idea of the completeness of the wave-mechanical account, and argued that the results of quantum experiments obtained in classical terms (as single values) are just *appearances* derivable from this account.

Schrödinger's interpretation, however, was confuted by Bohr. He agreed with Bohr's experimental critique based on the experiments with Compton's effect - performed by Compton and Simon and by Geiger and Bothe - that described the observed interactions in terms of ordinary classical particles. I suggest that it should be examined whether Everett's ideas and those of his successors can deal with the experimental evidence that Schrödinger found to be so strong against the universal wave-mechanical account of the physical world and which compelled him to acknowledge Bohr's points.

1. Schrödinger's 1926 Wave Theoretical Interpretation of Quantum Phenomena

In his ground-breaking 1913 paper,[1] Niels Bohr successfully applied Planck's quantum of action to Rutherford's classical picture of the atom (as a nucleus at the center of the elliptical orbits of electrons). One of the four assumptions of Bohr's theory stressed that ordinary mechanics suffices for the description of an atom in a stationary state.[2] Only *transitions* of the electrons from one orbit to another (i.e., from one stationary state to another) required invoking Planck's quantum of action.

It was precisely this abrupt transformation, this *space-time discontinuity*, which the electron, as an essentially classical particle in a stationary state, undergoes when the emission or absorption take place that Erwin Schrödinger found completely unsatisfying in Bohr's account. Schrödinger argued that a fundamental reformulation of Bohr's account was necessary "for we cannot really alter our manner of thinking in space and time, and what we cannot comprehend within it we cannot understand at all."[3] In a series of four papers published in 1926,[4] Schrödinger introduced characteristic frequencies (*E/h*) as the basic properties of interacting atomic systems, where the dynamics of atomic interactions is explained as a *resonance* phenomenon that does not defy space-time continuity.[5] The difference between the energies of two atomic states, explained by Bohr in terms of the electron's quantum energy jumps, results instead from the exchange of energies between two vibrating systems (thus preserving the space-time continuity of the process) characterized by appropriate modes of vibration.

Schrödinger stated his broader goal of reformulating the classical mechanical picture in order to make it fit quantum phenomena, by emphasizing the analogy between geometrical optics as opposed to optical processes as accounted for by the wave theory of light, on the one hand, and the mechanical processes described in terms of the motion of image points as opposed to wave processes, on the other.[6] Although the wave account of the nature of light discarded the ray approach,[7] it was not perceived to disagree with Maxwell's equations describing the electromagnetic field: Maxwell explained light as an electromagnetic disturbance propagating in the form of waves through the field. However, in dealing with very small wavelengths, Schrödinger argued, the classical mechanical equations describing the underlying mechanics of particle behavior in the electromagnetic field become as obsolete in accounting for the true nature of the micro-world8 as ray optics does in explaining the phenomena of diffraction:

We have seen that the same laws of motion hold exactly for such a signal or group of waves as are advanced by classical mechanics for the motion of the image point. This manner or treatment, however, loses all meaning where the structure of the path is no longer very large compared with the wave length or indeed is comparable with it. Then we *must* treat the matter strictly on the wave theory, *i.e.* we must proceed from the *wave equation* and not from the fundamental equations of mechanics, in order to form a picture of the manifold of the possible processes. 9

Instead of following the classical mechanical method of ascribing *n* particles to every point in *q*-space (a space with 3*n* coordinates through which wave disturbance propagates), each “particle” must be attributed a wave function. Thus, the nature of interactions in *q*-space can be thought of strictly in wave-mechanical terms.10 These interactions are different from those described by the laws of particle interactions, stretching one's imagination beyond the intuitions confined to the interactions within an ensemble of classical particles:

It is clear that then the “system path” in the sense of classical mechanics, *i.e.* the path of the point of exact phase agreement, will completely lose its prerogative, because there exists a whole continuum of points before, behind, and near the particular point, in which there is almost as complete phase agreement, and which describe totally different “paths”. In other words, the wave group not only fills the whole path domain all at once but also stretches far beyond it in all directions.11

Thus, the proposed manner of dealing with the shortcomings of classical mechanics with respect to very small dimensions and curvatures was to understand the ultimate physical units in terms of overlapping wave packages rather than in terms of well-defined particles. While outlining the need for his novel mechanics, Schrödinger emphasized *the holistic nature of the wave-mechanical spatio-temporal manifold*, specifying its impact on our understanding of the electron. Thus he argued the following:

" [I] explain the conviction, increasingly evident today, *firstly*, that real meaning has to be denied to the *phase* of electronic motions in the atom; *secondly*, that we can never assert that the electron at a definite instant is to be found on *any definite one* of the quantum paths, specialised by the quantum conditions; and *thirdly*, that the true laws of quantum mechanics do not consist of definite rules for the *single path*, but that in these laws the elements of the whole manifold of paths of a system are bound together by equations, so that apparently a certain reciprocal action exists between the different paths."12

Relying on experiments with the diffraction of light, the phase of the electrons' vibrations cannot be formulated in such a way as to represent the particle path, as it does in classical mechanics. Moreover, the meaning of the particle should be reinterpreted in accordance with the wave-mechanical formalism, which suggests the plural nature of its path.

2. Everett's Interpretation of 1954 and Its Fundamental Similarities with Schrödinger's Interpretation

In the closing chapter of his Ph.D. dissertation, which compared his interpretation of quantum mechanics with other interpretations, Everett explicitly stated that his own view "corresponds most closely with that held by Schrödinger."13 Although he did not specify whether this correspondence refers to Schrödinger of 1926 or to subsequent revisions of the interpretation that we will discuss shortly, Everett embraced the feature central to both of them, namely the wave function as "the fundamental entity."14 Thus, he approached the "measurement problem" as a problem of the relation between the state of *the observer as a physical system*, on the one hand,

and the state of *the observed physical system*, on the other. This relation can be satisfyingly explained by "pure" wave mechanics:

This paper proposes to regard pure wave mechanics ... as a complete theory. It postulates that a wave function that obeys a linear wave equation everywhere and at all times supplies a complete mathematical model for every isolated physical system without exception. It further postulates that every system that is subject to external observation can be regarded as part of a larger isolated system.15

Following the above-quoted postulate, Everett abandoned the standard take on the measurement problem, proposed by John Von Neumann.16 The standard interpretation treated the act of the measurement itself as causing the probabilistic system prior to turn into discrete and deterministic result (i.e., the measurement caused the wave function to collapse into one of the eigenstates).17 Instead, "[t]he general validity of pure wave mechanics, *without any statistical assertions*, is assumed for *all physical systems*, including observers and measuring apparata."18 Everett argued that the states of the observer and the measuring apparatus - which seemed to be unjustifiably treated as "special" by standard interpretation in that they are responsible for the actual outcome of the measurement - should be treated only as *relative to the state of the whole* which, as the wave-mechanical formalism shows, behaves continuously. (Similarly, Schrödinger insisted that "[w]e must start not from the fundamental equations of mechanics, but from a wave equation for *q*-space and consider the manifold of processes possible according to it..."19) Cutting up the system into two subsystems, one of which is then treated as the actual outcome of the measurement, is not physically justified. In his own words:

There does not, in general, exist anything like a single state for one subsystem of a composite system. Subsystems do not posses states that are independent of the states of the remainder of the system, so that the subsystem states are generally correlated with one another.20

Everett not only took seriously the moral of Schrödinger's holistic view of the micro-structures (the binding of different paths of particles by the equations),21 but also extended it to the measurement problem occurring at the macro-level. The interaction between the measuring device and the measured system acquires its physical meaning from the wave equation, and thus “it is meaningless to ask the absolute state of a subsystem - one can only ask the state relative to a given state of the remainder of the subsystem.”22 According to Schrödinger, as the “path” of a single particle lost its prerogative, it had to be understood as filled with a wave group extending in all directions. By the same token, Everett explained the relationship of the apparatus and the observed system in holistic terms, denying reality to the subsystem as a basic unit of the overall superposed system. Thus, the observed system only *appears* to the observer, who is external to the system, to be a set of subsequently existing atomic states. The *actual* configuration of the system is interpreted in terms of the superposition, as consisting of only tentatively elementary “particular eigenstates” corresponding to the states of the observer (the role very similar to the one performed by the normal modes of vibration at the micro-level) and related to each other according to the continuous wave function. As Everett put it:

…in each *element* of the superposition, ΦiΨi […,αi], the object-system state is a particular eigenstate of the observer, and *furthermore the observer-system state describes the observer as definitely perceiving that particular system state.*23

In this way, one could successfully avoid the assumption that shifts of the atomic system from one stationary state to another reflect the underlying discontinuous reality, and instead follow the formalism that suggests the continuous nature of the system.

The difficulty with the standard interpretation of quantum theory was not the only difficulty that Everett sought to overcome. He was also well aware both of the severe criticisms of Schrödinger's interpretation24 concerning the allegedly discontinuous atomic phenomena observed experimentally,25 and Schrödinger's failure to answer them satisfyingly. Everett expected that the *inclusion of the observation process in the wave interpretation* could successfully meet these criticisms as well. He was confident that two different groups of phenomena - the first directly related to Von Neumann's interpretation, “the *apparent* existence of definite macroscopic objects,” and the second, “localised phenomena, such as tracks in cloud chambers,”26 which turned out to be insurmountable obstacles for Schrödinger - were to be “satisfactorily explained in a wave theory,”27 but “only ... when observation processes themselves are treated within the theory.”

The literature on Everett's interpretation has typically failed to distinguish between these two groups of phenomena. The localisation demonstrated by tracks in cloud chambers, which Everett himself marked as a distinct group of phenomena that challenged wave-mechanical interpretations, had a distinct history. These may have a distinct bearing on the Schrödinger/Everett type of interpretations, and thus deserve distinct treatment. Indeed, as we will see shortly, the arguments of Bohr that convinced Schrödinger to renounce his interpretation in 1926 concerned the interpretation of these very phenomena. *What was it exactly about these experimental phenomena that led Schrödinger to renounce his 1926 interpretation*? *And was Everett justified in believing that his interpretation could successfully overcome the weaknesses of Schrödinger's interpretation in accounting for these phenomena?*28

3. Schrödinger’s Debate with Bohr: The Significance of Geiger-Bothe and Compton-Simon Experiments with Electron Scattering for the Failure of Schrödinger's 1926 Interpretation and Their Relevance to Everett’s Interpretation

Sometime between 1928 and 1929, Schrödinger apparently converted to the teachings of Bohr and Heisenberg,29 at least publicly, following his encounter with Bohr in the fall of 1926 and their subsequent correspondence. The vigorous debate ended with Schrödinger's defeat, mental exhaustion, and finally illness (which did not prevent Bohr from pushing his points forward!).30 Upon his return to Berlin, Schrödinger wrote Bohr that “in a certain sense I can say the psychological effect of these objections - in particular the numerous specific cases in which *for the present my views apparently can hardly be reconciled with experience* [*italics* - S. P.] - is probably even greater for me than for you.”31

What were these “specific cases” that Bohr pointed out to Schrödinger as experimental counter evidence to his wave-mechanical interpretation? At the time, Bohr had started doubting the theory that he developed with

Krämers and Slater. The Bohr-Krämers-Slater (BKS)32 theory attempted to reconcile continuity of the wave approach to quantum phenomena with the corpuscular approach that Einstein developed in 1906.33 Einstein's quantum-corpuscular theory was confirmed by Compton's experiments with X-rays, performed in 1923.34 Compton and others concluded that the light quantum distributes energy and momentum as a projectile, and not like a wave. According to a reconciliatory idea of BKS theory concerning the relation between radiation and atomic structure, an atom occupying a certain stationary state *communicates continually* with other atoms by means of a *virtual field*, similar to the field originating from the classical harmonic oscillators. Schrödinger himself was among the physicists who reacted very positively to this theory,35 praising a commitment to continuity that found its expression in communication between atoms in terms of virtual field. He also lauded its "fundamental violation of the laws of conservation of energy and momentum in each radiation process"36 – an aspect of the theory that he himself would bring to its final stage two years later with the abandonment of the physical meaning of the "path of the particle." Commenting on the notion of communicability in BKS, already in 1924 Schrödinger hinted at the philosophical grounds that he believed were appropriate for the development of the general theory of quantum phenomena, and that would be worked out in Everett's dissertation: "Thus one can also say: a certain stability in the world order sub specie aeternitatis can only exist through the interrelationship of each individual system with the rest of the whole world."37

However, the experiments performed by Compton and Simon (C-S) in 192438 and Geiger and Bothe (G-B) in 192539 led to the failure of the BKS theory. C-S, using the recently invented cloud chamber, demonstrated that *the momentum and energy of the electron could be shown to be preserved at any given time for individual processes*. The tracks left by the scattered X-rays demonstrated that the energy of X-ray quanta distributes in *definite directions*, as a projectile. Similarly, the experiments of B-G with electron coincidence techniques demonstrated that the chances of the coincidences of light quanta and recoil electrons appearances being accidental were very small, and that consequently *the electron must have determined momentum and energy*. Bohr was immediately aware of the disastrous impact of the results on the BKS theory as a moderate wave account of atomic interactions:40 the hypothesis of an atom communicating its energetic stationary states to surrounding atoms, and of the statistical interpretation of the laws of conservation of particle energy and momentum, had been contradicted experimentally.

Conceding the failure of his own expectation to explain the relevant experimental results41 in wave-mechanical terms, Schrödinger retreated publicly from pursuing his view but still hoped that it was only a matter of time before Bohr's ideas would be replaced by the wave-mechanical account.42 Indeed, in 1935 he started questioning the orthodoxy and subsequently reviving his original convictions.43 Robert S. Shankland's 1935 experiment with scattering in the gamma-ray region of the spectrum44 may have been the major boost for the revival.45 The results of Shankland's experiment allegedly conflicted with those of B-G and C-S and generated curiosity among Bohr and others. Schrödinger's Dublin seminar on interpreting quantum mechanics, which he delivered in the late 1940s and early 1950s,46 was largely a part of his effort to rearrange his wave-theoretical arguments in order to accommodate seemingly unfavorable experimental results. The view pursued in the seminar very often comes astonishingly close to Everett's interpretation. One of its consequences, clearly approaching Everett and most bluntly contradicting atomist intuitions, concerned the simultaneity of happenings in the universe containing matter distributed as waves. In Schrödinger's words:

Nearly every result [a quantum theorist - S.P.] pronounces is about the probability of this *or* that ... happening - with usually a great many alternatives. The idea that they be not alternatives but *all* really happen simultaneously seems lunatic to him, just *impossible*. He thinks that if the laws of nature took *this* form for, let me say, a quarter of an hour, we should find our surroundings rapidly turning into a quagmire, or sort of featureless jelly or plasma, we ourselves probably becoming jelly fish. It is strange that he should believe this. For I understand he grants that unobserved nature does behave this way - namely according to the wave function.47

However, the initial experimental boost for the revival finally ended with the repeated Geiger-Bothe and Compton-Simon experiments in the gamma-ray range of light, performed among others by Robert Hofsatdter and John A. McIntyre in 194948 and William G. Cross and Norman F. Ramsey in 1950.49 The results concurred "with simultaneity and the conservation of energy and momentum,"50 perhaps one reason that Schrödinger never published his Dublin seminar.

Being now acquainted with at least some of the experimental reasons that led Schrödinger to give up his interpretation of 1926, the following question remains: how can Everett's interpretation, being fundamentally similar to that of Schrödinger, account for the results of the C-S and G-B type experiments? Or to put it in more general terms, can any of the Everett-type interpretations51 account for the results? This paper illuminates the historical and interpretative grounds of these questions, but space constraints prevent us from answering them at this time. Preliminarily, developments in QED, and especially work on the so-called *second quantisation*, may prove highly relevant for further exploration.52

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2 Ibid.
3 E. Schrödinger, “Quantisation and Proper Values,” p. 27.
4 E. Schrödinger, *Collected Papers on Wave Mechanics*, New York: Chelsea Publishing Company, 1978.
5 E. Schrödinger, “Quantisation and Proper Values-I,” *Collected Papers on Wave Mechanics*, p. 10.
6 E. Schrödinger, “Quantisation and Proper Values - II,” p. 25.
7 Ray optics failed to account for the phenomena of light diffraction and interference and was replaced by wave theory by Fresnel in the XIX century.
8 This claim was grounded on experiments with the diffraction of light, such as the famous double-slit experiment.
9 Ibid., p. 25.
10 Schrödinger owes much to L. De Broglie's idea of matter-wave. However, he was dissatisfied with De Broglie's compromise with Bohr's account, where the whole numbers occurring in the expression for the phase-wave represented wavelengths corresponding to stationary states.
11 Ibid., p. 26.
12 Schrödinger, “Quantisation and Proper Values - II,” p. 26.
13 H. Everett, “Theory of the Universal Wave Function,” in B. S. DeWitt and N. Graham, eds., *The Many Worlds Interpretation of Quantum Mechanics*, Princeton: Princeton University Press, 1973, p. 115.
14 Ibid.
15 H. Everett, “‘Relative State’ Formulation of Quantum Mechanics,” in *Reviews of Modern Physics*, 29, 1957, p. 317.

16 J. Von Neumann, *Mathematical Foundations of Quantum Mechanics*, Princeton: Princeton University Press, 1955.
17 Everett, ibid., p. 3.
18 Everett, ibid., p. 8.
19 Schrödinger, "Quantisation and Proper Values," p. 27.
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21 Along the same philosophical lines that led Schrödinger to search for an alternative to Bohr's account that defied the space-time continuity, Everett stated that "[t]he 'quantum jumps' exist in theory as *relative* phenomena (i.e., the states of an object-system relative to chosen observer states shows this effect), while the absolute states change quite continuously." (Everett, "Theory of the Universal Wave Function," p. 115.).
22 H. Everett, "'Relative State' Formulation of Quantum Mechanics", p. 317.
23 H. Everett, "The Theory of the Universal Wave Function," 1973, p. 68.
24 I discuss this in Section 3.
25 Everett, ibid.
26 Ibid.
27 Ibid., p. 115.
28 I tackle the relation between Schrödinger and Everett and offer a detailed asnwer to the above-outlined question in an unpublished paper. In another unpublished paper I also develop the historical aspects of the Bohr-Schrödinger relation around 1926.
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30 Bohr, *Collected Works*, V. 6, pp. 10-11.
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33 A. Einstein, *Annalen Der Physik*, 20, p. 199, 1906.
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40 Bohr, *Collected Works*, V.5, p. 82.

41 Besides G-B and C-S experiments, Franck collisions and the Stern-Gerlach experiment must have been additional subjects of the Bohr-Schrödinger debate. See Pauli's and Heisenberg's correspondence in Bohr, *Collected Works*, V. 5.
42 Schrödinger in Bohr, ibid., p. 13.
43 E. Schrödinger, "Die gegenwärtige Situation in der Quantenmechanik," in *Naturwissenschaften*, 23, 1935, pp. 807-812.
44 R. S. Shankland, "An Apparent Failure of the Photon Theory of Scattering," in *Physical Review*, 49, 1936, pp. 8-13.
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50 Ibid., p. 2.
51 For an insightful discussion on different Everett-type interpretations see J. A. Barrett, *Quantum Mechanics of Minds and Worlds*, Oxford: Oxford University Press, 1999.
52 See P. A. M. Dirac, *Proceedings of the Royal Society*, 114 A, 1927, p. 243-265. Also, on Schrödinger's take "What is An Elementary Particle?" in *Science, Theory, Man*, NY: Dover Publishers, 1935. I deal with this issue in one of my aformentioned unpublished papers.