Foundations of Physics, Vol. 17, No. 12, 1987

Schrödinger and the Interpretation of Quantum Mechanics

Fritz Rohrlich[1]

Received April 2, 1987

On the occasion of the centennial of his birth, Schrödinger's life and views are sketched and his critique of the interpretation of quantum mechanics accepted at his time is examined. His own interpretation, which he had to abandon after a short time, provides a prime example of the way in which the tentative meaning of central theoretical terms in a new and revolutionary theory often fails. Schrödinger's strong philosophical convictions have played a key role in his refusal to break with many of the notions of classical physics. At the same time, they made him into a keen and incisive critic of the Copenhagen interpretation. His criticism is compared with present views on quantum mechanics.

1. INTRODUCTION

Erwin Schrödinger played a unique role in the development of quantum mechanics. Of the three acknowledged principal founders, Heisenberg, Dirac, and Schrödinger, he was by far the oldest,[2] and, apart from Einstein, the only one of all the founders (including Bohr, Born, Jordan, Pauli and others) who never accepted the so-called Copenhagen interpretation of the theory. He was thirty-nine years old, just two years younger than Bohr, when he wrote his seminal papers developing the equation that carries his name.

This fact provides a hint for his attitude toward the Copenhagen interpretation. But the important point necessary for an understanding of Schrödinger's singular position lies in views and convictions which he

[1] Department of Physics, Syracuse University, Syracuse, New York 13244-1130.

[2] At the time of the publication of his papers on wave mechanics, 1926, they were, respectively, 25, 24, and 39 years old.

0015-9018/87/1200-1205$05.00/0

formed relatively early in his scientific career and to which he adhered consistently throughout his life. They colored his interpretation of scientific theory in general, and they did not permit him to accept a radical revision of the classical understanding of physics as it became necessary with the emergence of quantum mechanics.

The present paper is written in appreciation of Erwin Schrödinger's contribution to physics on the occasion of the centennial of his birth. It will concentrate on the problems he encountered in developing his own interpretation of quantum mechanics and on his criticism of the conventional interpretation based on his deep philosophical convictions.

2. SCHRÖDINGER'S LIFE AND VIEWS

A full appreciation of Erwin Schrödinger requires at least a very brief sketch of his life and of the influences on him that helped shape his views. He was born in Vienna, Austria (August 12, 1887), the son of a chemist of wide interests from art to physiology; his mother was of British ancestry, the daughter of a chemistry professor. He received private tutoring until age eleven and then entered a humanistic "Gymnasium" (the equivalent of the American middle and high school but of much higher standards) where he received an excellent humanistic education (learning Greek and Latin) as well as a thorough grounding in science and mathematics. He obtained his "matura" (high school diploma) being at the top of his class throughout.

Later, he continued his humanistic studies on his own. As a result, it is only fair to say that it would be a rarity to find among today's scientists a person as well read and as knowledgeable as Schrödinger was. He knew ancient history[(1)] as well as a lot of philosophy including Indian philosophy. Throughout his life, he kept a strong interest in philosophical problems and he wrote on them repeatedly; he also wrote a volume of poetry.

During his student years at the University of Vienna (1906–1910), that institution was strongly influenced by the two well-known Austrian physicists (and philosophers!) Ernst Mach (1838–1916) and Ludwig Boltzmann (1844–1906). And his two dearest teachers at that time (Franz Exner and Fritz Hasenoehrl) were both former students of Boltzmann.

Ludwig Boltzmann was highly respected for his clear style of presentation, and his perspicuous lectures made a deep impression on his students.[3] Schrödinger wrote of him "His line of thought may be called my

[3] Schrödinger entered the University of Vienna just after Boltzmann's tragic death and thus knew him only through his writings.

first love in science. No other has ever thus enraptured me or will ever do so again."(2)

Exner later suggested (1919) that determinism on the microscopic scale is not a necessity and may even be not very likely. He raised doubts about the validity of conservation laws on the atomic scale and thus planted a seed in Schrödinger's mind that seems to have persisted most stubbornly to the end of his days: Schrödinger's last published physics paper is entitled "Might Perhaps Energy be a Merely Statistical Concept?"(3)

After earning his Ph.D. in 1910, he spent four years as an assistant to Exner. Then he served in the artillery during the First World War, during which (already in 1915) his beloved teacher Hasenoehrl was killed.

In 1918 (at the age of thirty-one), only four years after his "Habilitation" (the entrance lecture to a faculty position), he seriously considered accepting a chair in theoretical physics in Czernowitz (at that time part of the Austro-Hungarian empire) in order to devote himself, apart from giving lectures in physics, to philosophy.(4) But the events following the end of World War I prevented that.[4]

Schrödinger married in 1920 and spent the next two years at various universities (Jena, Stuttgart, and Breslau) advancing in the process to "ordinarius" (full professor). Then came his University of Zurich period of almost six years (1922–1927), during which he held the chair previously occupied by Einstein and by von Laue. This period included his "annus mirabilis" of 1926 (see Sec. 3 below). The presence there of Hermann Weyl became of great assistance to him on mathematical questions; Peter Debye helped direct him to the work of de Broglie. Toward the end of 1926, he also made a lecture tour through the United States.

This was followed by six years at the University of Berlin (1927–1933). The city of Berlin was the Mecca of physics. In that city lived and worked at that time Einstein, Planck, von Laue, Hahn, Meitner, Gustav Hertz, and Nernst among others. Schrödinger was called upon to occupy the chair vacated by Max Planck's retirement. That grand period of Schrödinger's life came to a sudden end with Hitler's rise to power. While Schrödinger was in no way affected by the Nazi racial laws, he resented that regime deeply, was quite outspoken about it and, in fact, opposed it openly. When many of his Jewish colleagues were forced to leave, he resigned in protest and went to England.

Soon after arrival at Magdalen College, Oxford, in 1933, he received word of having been awarded the Nobel prize jointly with Dirac. At

[4] The breakup of the Austro-Hungarian empire after the First World War placed the city of Czernowitz within the borders of Romania which became an independent state. Since the Second World War it has been part of the Soviet Union.

Oxford he wrote his critique of quantum mechanics (Sec. 4 below). But after three years in England, homesickness made him return to his native Austria and to accept a position at the University of Graz, where his venerated example, Ludwig Boltzmann, had taught for many years before coming to Vienna. That return soon proved to have been a bad mistake: The Nazi regime caught up with him. Soon after the annexation of Austria in March 1938, he was forced to flee; he escaped[5] by an adventurous journey to Italy.

Luck intervened: the Prime Minister of Ireland, Eamon de Valera, himself a physicist and proud of the important role that the great Irishman Sir William Rowan Hamilton played in Schrödinger's thinking during the genesis of wave mechanics, invited him to join the Institute of Advanced Studies in Dublin. He stayed there from 1940 to 1956. Despite repeated urging from the University of Vienna after the Second World War, he remained true to his convictions and did not move back to Austria to accept that invitation until the Soviet occupation had left and Austria was free again in 1956. But ill health set in soon thereafter and he had several relatively inactive years. He died in 1961 (on January 4th). According to his wishes, he was buried in the beautiful little Alpine village of Alpbach in Tyrol.

It is clearly not even remotely possible to do justice here to Schrödinger's philosophical beliefs. I shall sketch but a few of his pertinent views. His consistency in advocating these views is remarkable, as can be seen easily from a comparison of his two philosophical papers "Seek for the Road" (1925, before he started work on the wave equation) and "What is Real?" (1960, the year before his death).[(4)]

Contrary to common belief, he was not a scientific realist. In fact, his views in some respect were not very far from those of Boltzmann, who wrote:[(5)]

> "... the task of theory consists in constructing a picture of the external world that exists purely internally... ."

Schrödinger did not accept an external reality to which the central terms of a physical theory refer. He believed in physical reality in a different sense; and he also believed in the possibility of an objective description of it: In his view, that reality is in the mind. He wrote:[(3)]

> "... the so-called external world is built up exclusively of constituents of the ego."

and

> "... The widespread attitude that the claim of an objective description of physical reality must be given up, is rejected on the ground that the so-called

[5] With hand luggage only.

> external world is built up exclusively of elements of the single mind, and is characterized as what is common to all, recognized by every healthy and sane person... ."[3]

Thus, his realism is more a "rational mysticism"[6] or at best a "methodological realism."[7] The experience of an external world is only an occurrence in the mind. And beyond that, Schrödinger believed in the commonality of the individual minds: there is really only one mind; the plurality we perceive is only an appearance.[4] He took this notion from the Vedantic philosophy.

When it comes to doing science, Schrödinger had guidelines that were strongly based on the concepts of classical physics:

> "... the representation of a physical process in a mental picture must be free of space-time gaps, i.e., the picture must at least in principle allow one to say what is happening at every moment at every point of space."[8]

Is it then surprising that he objected to the notion of discontinuities and quantum jumps? He wrote a long nontechnical paper,[9] based on an earlier technical one,[10] arguing against them; he likened quantum jumps to the epicycles of Ptolemy, and he talked of "the nightmare that physical events consist of continual sequences of little fits and jerks."[9] He believed that the emission and reabsorption of a photon should be regarded as a resonance phenomenon characterized by the equality of the frequency differences (corresponding to the energy level differences) of the emitting and the absorbing atom.

There can be therefore no surprise at his objection to the whole approach of the accepted interpretation of quantum mechanics:

> "A widely accepted opinion claims that an objective picture of reality—in the sense we used to believe it—cannot exist at all. Only the optimists among us (among whom I include myself) consider this to be a philosophical eccentricity, an act of desperation in the face of a great crisis."[11]

Schrödinger delighted in the support he received in this respect from Einstein, although the latter was motivated by quite different considerations. Their correspondence bears witness to their common concerns.[12]

Schrödinger's strong philosophical convictions were pretty well established *before* he started his work on wave mechanics (late in 1925). His intellectual honesty did not permit him to deviate from these. No matter what mathematical results his scientific research led to, he felt that they must be interpreted in the spirit of the philosophical views he held. As we shall see, despite his repeated failures in finding an interpretation of quantum mechanics to his satisfaction, he remained true to his convictions to the end.

3. THE ELECTRODYNAMIC INTERPRETATION

The reasons for Schrödinger (rather than somebody else) to have been motivated by de Broglie's work and to have developed wave mechanics have been studied at length.[13] Similarly, his conceptual approach to wave mechanics has been explored by several authors.[2,7,14] I shall therefore not discuss these matters. But I do want to focus on the physical interpretation which he gave in his papers of 1926.[15]

From that year on, several semiclassical interpretations of quantum mechanics arose. They are described in detail by Jammer.[2,16] Schrödinger's own interpretation based on his wave mechanics was presented primarily in his fourth paper of "Quantization as an Eigenvalue Problem": Quantum mechanics is a classical theory of waves; these are the fundamental ontological objects; matter is, in the last analysis, a complicated superposition of them. These "matter waves" are *continuous* functions of space and time. Furthermore, the continuity equation which is easily derivable from the free Schrödinger equation suggests an electromagnetic interpretation of the wave function ψ: The charge density of the electron is to be identified with the electron charge e times $\psi^*\psi$, and the electric current density is the corresponding expression $e\hbar(\psi^* \nabla\psi - \psi \nabla\psi^*)/2mi$. The theory is, however, only *semi*classical because of the quantization involved, which provides for the stability of the charge distribution of the electrons in the atom; this distribution cannot be stable classically.

After more than sixty years of quantum mechanics, we can claim to understand it now fairly well, even though some problems are still unsolved; and with this hindsight we can also assert that Schrödinger at that time did not know what he was talking about. This is not meant as an indictment. Heisenberg did not understand matrix mechanics either in 1925, two years before he had the uncertainty relations. Nor did Einstein's view of reality apply to quantum mechanics as he had expected. And, for that matter, Newtonian mechanics is conceptually different from Newton's mechanics of the *Principia* with its absolute space and time; and electrodynamics today differs from Maxwell's electrodynamics with his mechanical ether. It is the normal state of affairs at the beginning of a revolutionary theory.[6]

There was, however, an essential difference between Schrödinger and Einstein, on the one hand, and the Copenhagen group and its immediate supporters, on the other: Heisenberg, Dirac, Jordan, and Pauli were all in

[6] Einstein vis-a-vis his two theories of relativity must here be considered to be an exception.

their mid-twenties and were not set in their world view.[7] They were willing to follow wherever their research led them, even if it meant giving up cherished old ideas of previous generations of physicists. At this point the greatness of Niels Bohr is evident: He was not only able to go along with that revolution but even to lead it successfully despite his age (then over forty). Also Max Born (three years older than Bohr) must be noted here: He provided one of the radical breaks with tradition when he proposed the probabilistic interpretation.

Difficulties of Schrödinger's interpretation were apparent almost immediately. Some of them were noted by Schrödinger himself, others were pointed out to him by some of the leading physicists of the time, much of it already in 1926. Thus, Lorentz wrote a long letter to Schrödinger (eleven tightly written pages) asking, among other questions, (1) how the spreading of the wave packet can be compatible with the identification of wave packet and particle, (2) how the wave function can descibe a wave in ordinary three-dimensional space when its configuration space has more than three dimensions, and (3) how a single electron in the photoelectric effect is pried loose from the complex superposition of matter waves that make up the charge distribution of all the electrons in an atom. Heisenberg questioned whether Schrödinger's interpretation would permit a derivation of Planck's law of black-body radiation. And Schrödinger himself noted that (1) since the wave function is complex, it must represent two real waves, and (2) there is an inconsistency between the continuous charge distribution of the electron in the hydrogen atom and the use of Coulomb's law for point particles in his equation for H.

Schrödinger's electrodynamic and semiclassical interpretation was in competition not only with Born's probabilistic interpretation[(17)] (published already in July 1926), which quickly became part of the Copenhagen interpretation (Born was in Göttingen). A hydrodynamic interpretation was published soon thereafter by Madelung, and de Broglie's interpretation also appeared in the same year. Each of these interpretations raised different questions and exhibited true or apparent difficulties. But the Copenhagen group seems to have acquired the plurality if not the majority of supporters. This seems to have become especially evident after Bohr spoke on his complementarity concept (Como conference, September 1927) and Heisenberg on his uncertainty relation (Solvay conference, October 1927) which he had published earlier that year.[(18)] The Bohr–Einstein debates which started at that Solvay conference (which Schrödinger attended) indicated how seriously Einstein took the

[7] Because of their age, quantum mechanics was at that time dubbed "Knabenphysik" (the physics of young boys).

Copenhagen view; they added considerable additional credence to that view as compared to the other interpretations, including Schrödinger's.

But Schrödinger did not admit defeat publicly until late in 1927.[7] He shared with Einstein a permanent opposition to a probabilistic interpretation, admitting only the untenability of his own classical ontic wave picture and electromagnetic interpretation. This defeat jolted his views severely; he wrote:

> "Insofar as the basic assumptions of quantum theory hold true, arbitrarily fine observations are impossible.... This realization, which we owe to Heisenberg, strikes deep, deep, into our physical world picture; it alters the conception of what should even be understood as a physical picture of the world."[19]

What has happened is simply this. A revolutionary new theory was formulated at first mathematically; it became accepted because of its great success in accounting for empirical data not previously accounted for (in this case, primarily the hydrogen spectrum and then the implications of the equivalence to Heisenberg's matrix mechanics, proven first by Schrödinger in 1926.[20] But the *interpretation* of the central terms of that theory was not assured by that process alone. It is possible (and in fact happens quite often) that the mathematics is done right but that the interpretation of it is done incorrectly. And that is true quite generally for the case of revolutionary theories. Recollecting those early days of quantum mechanics, Dirac said:[21]

> "This problem of getting the interpretation proved to be rather more difficult than just working out the equations."

The first and most natural attempt at an interpretation of a radically new theory consists in the attempt of carrying over old and well-established concepts as much as possible. Only when that fails is one forced into new and often strange concepts. Schrödinger's interpretation had to be considered and tried before it could be discarded. And the same was true of other proposals.

Schrödinger's admission of defeat concerning his understanding of quantum mechanics was for him also the beginning of a quest for a (to him) satisfactory interpretation of quantum mechanics, since he was unwilling (based on his philosophical convictions) to accept the Copenhagen view. He struggled with this problem off and on for the rest of his life. Despite his clarity concerning his objections to the accepted interpretation, he was unable to do better.

4. THE CRITIQUE OF THE COPENHAGEN INTERPRETATION

Let us now turn to the years 1935–1936. First, the famous critique of quantum mechanics by Einstein, Podolsky, and Rosen was published.[22] As is well known, it was an argument which claimed to prove that quantum mechanics is not a complete theory. It was based on a seemingly very reasonable definition of reality (or element of reality) with which Schrödinger was presumably in full agreement. He had considerable correspondence with Einstein already in 1926 before he joined him in Berlin, and he resumed it after both had left there. The topic was often their common objections to the then generally accepted interpretation of quantum mechanics.[12] The Einstein–Podolsky–Rosen (EPR) paper was therefore a natural stimulation for him to express his own views on the subject in the form of a scientific journal article. In fact, he wrote two technical papers[23,24] and one long nonmathematical article, spelling out in detail his objections to the accepted interpretation.[25] The latter makes use of some of the results obtained in the technical papers but contains a great deal more and is also much better known; it is popularly referred to as the "cat-paradox" paper, even though this item is only a one-paragraph side remark in that very long paper. These three articles appeared only months after the EPR paper. In a footnote (Ref. 25, p. 845), Schrödinger acknowledges his debt to that paper and wondered whether his own paper should not be called a "general confession." He had obviously felt burdened by his objections to quantum mechanics for a long time, and one has the impression that he regarded the Copenhagen interpretation somewhat like "the emperor's new clothes."

The topic of the two technical papers is the notion of "entanglement." This is the term used by Schrödinger for the situation (known to everyone acquainted with quantum mechanics) that arises whenever the wave function of two noninteracting particles is not the product of wave functions of the two separated particles but the sum of such products. The simplest example is the singlet state of two spin-1/2 particles, $\psi(1,2) = (1/\sqrt{2})(\psi_+(1)\,\psi_-(2) - \psi_-(1)\,\psi_+(2))$; the subscripts + and − refer to the z component of spin. Measuring particle 1 and finding it to have spin up (+) ensures one that particle 2 will after that measurement be in the state of spin down (−) (both referring to the same z axis). This can be verified by a measurement on particle 2. While this is a seemingly trivial consequence of angular momentum conservation in the z direction, it is not trivial when one notes (a) that neither particle 1 nor particle 2 were *before* that measurement in a state of definite up or down spin, (b) that the choice of the z axis along which the measurement is made is completely arbitrary, and (c) that the two particles are noninteracting and can be arbitrarily far apart at the time of the measurement. The typical student in a quantum mechanics class usually accepts all this without objection or even surprise.

More sophisticated results emerge when the spin polarization directions for the measurements on particles 1 and 2 are chosen to make a finite angle. One observes quantum correlations that differ[8] from those expected from Einstein's local definition of reality.[(26)]

Neither Schrödinger nor Einstein were willing to accept entanglement without serious reservations. The two papers by Schrödinger[(23,24)] had the goal of carrying that notion *ad absurdum*. He showed that one can construct sufficiently complicated wave functions, and one can devise suitable measurements, so that a measurement on particle 1 will cause particle 2 (an arbitrary distance away) to go into any arbitrarily chosen state (within reason) with a finite probability. Schrödinger speaks of steering at a distance. He puts it this way: "It is rather discomforting that the theory should allow a system to be steered or piloted into one or the other type of state at the experimenter's mercy in spite of his having no access to it." Needless to say, neither he nor Einstein ever seriously considered action at a distance as an explanation; they found entanglement completely unacceptable and blamed it on the unsatisfactory nature of quantum mechanics.

The phenomenon of entanglement was also at the base of the EPR paper, as can best be seen from Bohm's version of their thought experiment;[9] but Schrödinger carried it much further in his papers (Ref. 23 and 24). And he included that issue also in the paper on "the present situation in quantum mechanics,"[(25)] but there it occurs only near the end, and the EPR paper is cited as an example. The paper starts out by observing that quantum mechanics claims determinism to be impossible so that (in Schrödinger's mind) the question of reality is raised immediately; how can reality not be deterministic at least *in principle* (as in statistical mechanics)? Furthermore, since only half the classical phase space can be sharp at any one time (either the x's or the p's), is the other half then not real? The notion of a "blurred reality" is unacceptable to him.[10] Alternatively, is it possible that the blurred variables are real but that the

[8] This is the essential point of the famous Bell inequality.

[9] Bohm replaced the EPR thought experiment by an equivalent but practically workable one: Two spin-1/2 particles are created in a singlet state and emerge in opposite directions; the measurement of the spin polarization in a chosen direction (in the plane orthogonal to the direction of motion) on particle 1 will then determine a certain probability of finding the spin of particle 2 up (or down) along any other direction (in a plane orthogonal to its direction of motion). This experiment can be carried out with essentially the same results also for a pair of photons. The latter was used in Ref. 26.

[10] He prefaces the notion "blurrred reality" by *sit venia verbis*, "pardon the expression" (literally: may forgiveness be [given] for the words).

theory does not tell us what they are? And he then goes on to argue that "blurring" is impossible.

His argument states that reality must also be given to what is described as blurred because it has macroscopically tangible effects. He offers two examples: α-particle decay and the cat. In α decay one has a spherical wave emerging from the nucleus–the blurred description of the α particle. But any detection device will locate that particle at exactly one point, the classical case of the localization of a particle. Since the particle is therefore *real*, it should not be described as blurred, so that quantum mechanics is consequently providing an unsatisfactory description.

His second example is (by his own words) a "burlesque case." It is the well-known case of a cat being killed by a device triggered by a radioactive decay so that there is a fifty-fifty chance of it being killed within a given time. He concludes that therefore quantum mechanics describes the cat as a linear superposition of two wave functions ψ(live) and ψ(dead). Since this is patent nonsense, the quantum mechanical description has been carried *ad absurdum.*

He then goes on to blame quantum mechanics for solving the problem of blurring by an epistemological trick: It accepts only what is directly observable and does away with all questions of ontology beyond that (extreme empiricist view). Quantum mechanics is being accepted only as a computational scheme; it only relates experimental results with one another. What is not known via quantum mechanics is considered not knowable (extreme instrumentalist view). These accusations were clearly made against the Copenhagen interpretation as he understood it.[(27)] He considered this view as a dictator brought in at a time of dire lack of physical methodology.

Schrödinger also objected to a certain holism implied in quantum mechanics: The entangled description implies that the maximal knowledge of the whole system does not imply maximum knowledge of the parts of that system even when these parts are noninteracting. This fact, he concluded, makes a description in terms of a wave function unsuitable as a model of reality. Furthermore, that wave function undergoes a discontinuous change during measurements, while nature is continuous (one of his most fundamental beliefs.)[11]

The conclusion Schrödinger draws from all this criticism is that, despite its great success, quantum mechanics should be regarded as a clever computational scheme rather than as a fundamental theory.

[11] I have elaborated on other points of this paper elsewhere (see Ref. 27), but the above provides a fair sample of Schrödinger's critique.

5. TODAY'S PERSPECTIVE

In the twenty-five years that elapsed between the time he wrote this critique and the time of his death, Schrödinger tried in vain to improve upon the interpretation of quantum mechanics which he so severely criticized. There was never any doubt in his mind that such an improvement is possible and that his basic philosophical views will eventually be borne out. His last published paper[(3)] and his 1960 world view[(4)] bear witness to his tenacity and his fidelity to the views he held throughout his life.

From today's vantage point, one may well be inclined to discard his criticism of quantum mechanics as outdated and irrelevant, and one may claim to know better. This position would be a rash and unjustified verdict based on a considerable overestimation of what we actually understand well today. To demonstrate this point, I shall very briefly compare Schrödinger's critique with our present understanding of quantum mechanics.

First, it is notable that an empiricist-instrumentalist view still exists among some scientists today. That interpretation was much easier to maintain in the twenties and thirties, when logical positivism dominated the philosophy of physics. I believe, however, that most physicists today no longer share this view. In this respect, most of us therefore fully agree with Schrödinger's objections to that view.

The other extreme view is held by even fewer people today. It is the view that there exists a deterministic structure underlying quantum mechanics. This interpretation is partly based on the old fluid flow interpretation by Madelung and was further developed and strongly advocated by Bohm and some of his followers. It received a severe blow[12] from recent experiments[(26)] but it is not so far empirically or logically excluded.[(28)] To the best of my knowledge, neither Schrödinger nor Einstein ever subscribed to this hidden-variables view, even though they were sympathetic to an in-principle deterministic view ("God does not play dice").

It is unfortunate that those not actively working on fundamental questions usually do not have a consistent and clear view on the interpretation question. They believe in a mixture of an instrumentalist and a realist view as implied by most textbooks, and they would have difficulties giving satisfactory answers to the questions that Schrödinger raised more than half a century ago. But even those who have been working on the foundations of quantum mechanics admit that still today some questions

[12] There is a small loophole[(28)] in the conclusions of the Paris experiment,[(26)] and *nonlocal* hidden-variables theories are not excluded.

raised by Schrödinger remain unresolved, while others have been apparently settled but not to everyone's satisfaction. In particular, the "collapse" or reduction of the wave packet is still not fully understood, even though there exist a number of seemingly reasonable proposals.

I believe that the large majority of physicists are at least intuitively scientific realists believing in the actual existence of fundamental particles and generally in an external world independent of human ability to observe it. But they have difficulties reconciling this view with some of the demands of quantum mechanics. For this reason, the interpretation called "quantum realism" may well become the accepted interpretation of quantum mechanics.[29-31] To this end, the reduction problem would have to be resolved in a way consistent with that view. Scientific realism extended to quantum realism is one of the very few internally consistent interpretations and seems at present to be the one most likely to succeed in the long run. I shall therefore compare *it* with Schrödinger's view.

The interpretation of the wave function as a collection of *potentialities* was first suggested by Heisenberg.[32] After Schrödinger had to give up his original classical wave interpretation of wave mechanics, there is every reason to believe that he was willing to accept Born's probability interpretation, provided only that it is not understood to mean indeterminacy *in principle* and that his other objections related to it (entanglement and blurring) could be satisfactorily resolved. Thus, after 1927 Schrödinger would have accepted Heisenberg's review of potentialities with these reservations emphasizing that quantum mechanics is *not complete* and is therefore not a fundamental description.

Schrödinger of course did not know of the experimental confirmation of entanglement.[26] In the quantum realist interpretation these empirical results force us into accepting the notion of *nonseparability* even though this is a most unintuitive concept. Distant and noninteracting components of a quantum system (typically indistinguishable particles) described by an entangling wave function are nonseparable: They act as one system in the sense that a measurement of one of the components affects the whole system together (nonlocal nature of the system). The obvious response of fear that special relativity be violated turns out to be unfounded. One can prove[33] that this is not the case: It does not violate causality in the sense of requiring signal velocities faster than light. No signals (no energy transfer) are involved. Schrödinger's "steering at a distance" is therefore an experimental fact that has to be included in the interpretation. Though perhaps unintuitive, one must yield to this powerful combination of empirical evidence and mathematical proof, and one is forced to accept nonseparability. Schrödinger would have done so too, and his concerns about entanglement would thus have been laid to rest.

Finally, what is perhaps the most difficult new notion, the concept of "blurring," must in this realistic interpretation be given an ontic meaning. To this end, there is no choice but to accept a new category of existence: The spherical wave emerging from the nucleus describes an actually existing α particle in a blurred state (without specific location). The state is then changed by the detector into a localized state. The blurring of position in no way detracts from the actual existence of a quantum particle, which is essentially a point particle. This is in contradistinction to the classical case where no such blurring can occur for real particles even though we may *in practice* not be able to localize it (classical statistical mechanics). Similar statements hold for other properties than position which can experience blurring.

Here, then, is a new concept which Schrödinger would most likely not have embraced. His classical world picture was too well set for that. But we see from the above how far, it would seem, he would have been willing to go when confronted with what we know today. His penetrating criticism was very much to the point, his insight deeper than that of most physicists of his time.

* * *

This study has emphasized Schrödinger's work on quantum mechanics. By doing that, we did not mean to ignore his very broad interests in physics and science in general. His work in statistical mechanics (including a book on the subject[(34)]) started well before his work on wave mechanics.[13] During his Dublin years he worked extensively on general relativity and on the problem of finding a unified field theory.[(35)] And he also wrote at that time the delightful little book *What is Life*? in which he set down his views on the reduction of biology to physics and chemistry.[(36)]

Schrödinger was a very great scientist and a deep thinker. We are very much in his debt for his many valuable contributions to physics and for setting an example to us in intellectual honesty.

REFERENCES

1. E. Schrödinger, *Nature and the Greeks* (Cambridge University Press, Cambridge, 1954).
2. From Schrödinger's speech at the occasion of his inauguration to membership in the Prussian Academy of Science, 1929, as quoted by M. Jammer, *The Conceptual Development of Quantum Mechanics* (McGraw-Hill, New York, 1966), p. 255.
3. E. Schrödinger, *Nuovo Cimento* **9**, 162–170 (1958).
4. E. Schrödinger, *My View of the World* (Cambridge University Press, Cambridge, 1964).

[13] His study of Einstein's 1925 paper on gas dynamics in fact made him first aware of the importance of de Broglie's ideas.[(14)]

5. L. Boltzmann, *Theoretical Physics and Philosophical Problems* (D. Reidel, Dordrecht, 1974), pp. 33 and 65.
6. B. Bertotti, "The later work of E. Schrödinger," *Stud. Hist. Philos. Sci.* **16**, 83–100 (1985).
7. L. A. Wessels, *Schrödinger's Interpretation of Wave Mechanics*, Ph.D. Dissertation, Indiana University, 1975.
8. E. Schrödinger, *Naturwissenschaften* **17**, 486–489 (1929).
9. E. Schrödinger, "Are there quantum jumps?" *Br. J. Philos. Sci.* **3**, Part I: 109–123, Part II: 233–242 (1952).
10. E. Schrödinger, "Energieaustausch nach der Wellenmechanik," *Ann. Phys. (Leipzig)* **83**, 956–968 (1927).
11. E. Schrödinger, *Was ist ein Naturgesetz*? (R. Oldenburg, Muenchen, 1962), p. 102 (my translation).
12. K. Przibram, *Briefe zur Wellenmechanik* (Springer-Verlag, Wien, 1963).
13. V. V. Raman and P. Forman, "Why was it Schrödinger who developed de Broglie's ideas?", *Hist. Stud. Phys. Sci.* **1**, 291–314 (1969).
14. L. Wessels, "Schrödinger's route to wave mechanics," *Stud. Hist. Philos. Sci.* **10**, 311–340 (1979).
15. E. Schrödinger, *Collected Papers on Wave Mechanics* (Chelsea, New York, 1982); contains a translation of his four original papers as well as later papers and four lectures.
16. M. Jammer, *The Philosophy of Quantum Mechanics* (McGraw-Hill, New York, 1966).
17. M. Born, "Zur Quantenmechanik der Stossvorgaenge," *Z. Phys.* **37**, 863–867 (1926). It is to be noted that this first of several publications about the probabilistic interpretation by Born contains the crucial point (that $\psi\psi^*$ rather than $|\psi|$ is to be interpreted as a probability) only as a footnote.
18. W. Heisenberg, "Ueber den anschaulichen Inhalt der quantentheoretischen Kinematik und Mechanik," *Z. Phys.* **43**, 172–198 (1927).
19. E. Schrödinger, "Neue Wege in der Physik," *Elektrotech. Z.* **50**, 15–16 (1929).
20. E. Schrödinger, "Ueber das Verhaeltnis der Heisenberg–Born–Jordanschen Quantenmechanik zu der meinen," *Ann. Phys. (Leipzig)* **79**, 734–756 (1926).
21. Quoted by A. Pais, *Inward Bound* (Clarendeon Press, Oxford, 1986), p. 255.
22. A. Einstein, B. Podolsky, and N. Rosen, "Can quantum-mechanical description of physical reality be considered complete?" *Phys. Rev.* **47**, 777–780 (1935).
23. E. Schrödinger, "Discussion of probability relations between separated systems," *Proc. Camb. Philos. Soc.* **31**, 555–563 (1935).
24. E. Schrödinger, "Probability relations between separated systems," *Proc. Camb. Philos. Soc.* **32**, 446–452 (1936).
25. E. Schrödinger, "Die gegenwaertige Situation in der Quantenmechanik," *Naturwissenschaften* **23**, 807–812, 823–828, 844–849 (1935). A translation can be found in J. A. Wheeler and W. H. Zurek, *Quantum Theory and Measurement* (Princeton University Press, Princeton, 1983).
26. A. Aspect, P. Grangier, and G. Roger, *Phys. Rev. Lett.* **49**, 91 (1982); A. Aspect, J. Delibart, and G. Roger, *Phys. Rev. Lett.* **49**, 1804 (1982).
27. F. Rohrlich, "Schrödinger's criticism of quantum mechanics—fifty years later," pp. 555–572, in P. Lahti and P. Mittelstaedt, eds., *Symposium on the Foundations of Modern Physics, Fifty Years of the Einstein–Podolsky–Rosen Gedankenexperiment* (World Scientific, Singapore, 1985).
28. N. D. Mermin, "The EPR experiment—thoughts about the loophole," pp. 422–427, in D. M. Greenberger, *New Techniques and Ideas in the Quantum Measurement Theory* (New York Academy of Science, New York, 1987); *Ann. N. Y. Acad. Sci.* **480**, 422–427 (1986).

29. A. Shimony, "Metaphysical Problems in the Foundations of Quantum Mechanics," *Int. Philos. Quarterly* **18**, 2–17 (1978).
30. A. Shimony, "Reflections on the Philosophy of Bohr, Heisenberg, and Schrödinger," pp. 305–317, in R. S. Cohen and M. W. Wartofsky, *A Portrait of Twenty Five Years, Boston Colloquium for the Philosophy of Science 1960–1985* (Reidel, Dordrecht, 1985).
31. F. Rohrlich, "Reality and Quantum Mechanics," pp. 373–381 in Ref. 28.
32. W. Heisenberg, *Philosophy and Physics* (Harper, New York, 1958), especially p. 185.
33. M. L. G. Redhead, "Relativity and quantum mechanics—conflict or peaceful coexistence?" pp. 14–20 in Ref. 28.
34. E. Schrödinger, *Statistical Mechanics* (Cambridge University Press, Cambridge, 1948).
35. E. Schrödinger, *Space-time Structure* (Cambridge University Press, Cambridge, 1963).
36. E. Schrödinger, *What is Life?* (Cambridge University Press, Cambridge, 1944).