On the Status of Hidden Variable Theories in Quantum Mechanics

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1. Quantum theory vs. hidden variables

It takes time for new paradigms to be generally digested and become known. It also takes time to change some of the old paradigms once they have been used for some time. So one has become accustomed to the conclusion, although deeply disturbing, that no hidden variable models can be introduced into quantum theory, *i.e.*, there is a limit to our knowledge. One cites Bell's theorem and all the discussions taking place around this theme, notwithstanding the example of D. Bohm's trajectories. I want to show that the confrontations between standard quantum theory and hidden variable models has not been resolved once and for all, as many now think. On the contrary, there are very simple physical "hidden" variable models—not so "hidden", actually—which provide a deterministic quantum mechanism, such that the standard probabilistic quantum mechanics is obtained after an average over an ensemble.

It is like the paradigm of quarks as real physical constituents of hadrons, rather than group theoretical objects: very unnatural. It took a long time to get accustomed to this, but once one has become accustomed to them, it is very difficult to get across the idea that the real constituents of matter cannot be quarks.

Bell's theorem is, of course, mathematically correct, but it has in it an implicit, tacit assumption about what hidden variables one is actually looking for. One already assumes what the single individual event is, namely, a spin that can have only two values, or a photon that can be detected or not, both dichotomic variables. The single events already have quantum properties. One thinks that if the light intensity is lowered down sufficiently one ends up with an individual single photon, whereas the photon is a statistical notion. One can calculate a Feynman probability amplitude *as though* light consisted of photons of various frequencies. It is not that each single atom emits a single photon (it could not, because the photon fills the whole space!). Similarly, a single individual electron cannot already have a quantized spin, up or down; it can have a spin vector pointing in any direction, but only for an ensemble can the average direction relative to some axis be up or down, or for a beam of electrons, 50% spin up and 50% spin down, for example. This is the meaning of an "entangled" state. An individual electron cannot be in an entangled state; only an ensemble can. Thus, an *extrapolation of a statistical property onto a single individual* is the cause of a great deal of confusion, as the following example shows: a population can be 50% male and 50% female, but a single individual cannot be 50% male and 50% female.

We have calculated all quantum correlations, as well as interference phenomena using individual events with classical "hidden variables" and obtained quantum results after averaging over these parameters. In the case of spin, the classical (hidden) parameters are the angles of the spin direction, in the case of interference, the initial position and velocity of localized solutions of the wave equation, called wavelets. The individual wavelets propagate according to the propagator of the wave equation, and then one averages over the initial conditions of the wavelets. This procedure is similar to Bohm's trajectories or Feynman path integrals. But each wavelet-motion is a possible physical event.

How odd it is that the situation in quantum mechanics with respect to hidden variables is characterized as a "mystery" or "paradox," and yet one tries to make this mystery permanent, perhaps in the hope that something new will be discovered. But one tacit assumption is never questioned, not even stated as an assumption: namely, the nature of a single event, the individual spin or individual light signal in the hidden variable model. In all discussions of the Bell inequalities and all related issues, an individual spin already has a quantum property, a property of two-valuedness which we know holds only for the typical property in an ensemble (as an average).

It is true that in a Stern-Gerlach experiment with individual spins, one after the other, each spin will be exactly ±½. On the average, yes, but not necessarily individually, one obtains a distribution with two broad maxima. Only a small deviation from two short lines is sufficient to restore quantum conditions from classical hidden variable models.

That the assumption of the dichotomous nature of individual spin is not correct can be seen from the fact that it leads to incomprehensible mysteries, and paradoxes, and hence must be abandoned. On the other hand, the individual spin as a direction, with classical parameters (q, j) as hidden variables, leads to the correct result.

An argument often given against hidden variables or deterministic wave mechanics is that for many-particle systems, the quantum wave function is in configuration space and not in ordinary space, and hence not *a priori* intuitive. But the formulation in configuration space does not preclude starting from individual wave functions for particles in ordinary space. If one varies the action with respect to the product of individual functions one obtains a linear equation in configuration space, but if one varies the action for individual wave functions one obtains the set of coupled nonlinear Hartree equations. The configuration space (mathematically the result of the tensor product postulate of the Hilbert spaces of subsystems) implies more directly some long range correlations, and symmetries of identical particles (Pauli's principle), than the Hartree equations.

2. Future developments of foundations

I think the most important problem is not in quantum mechanics *per se*, but in quantum electrodynamics and the theory of the electron. We have to study the structure of the electron, and if possible, the single electron, if we want to understand physics at short distances. Of course, one can introduce a lot of phenomenological particles and new forces, as is done in high energy physics. But this is not the only possibility. There are arguments that the extrapolation of electrodynamics to short distances might shed new light on high energy phenomena in that they are of electromagnetic nature.

The completion of a deterministic quantum theory, the extrapolation of a non-perturbative electrodynamics to short distances to see if the particle physics phenomenology comes out, as it seems, are the most important problems.

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Fundamental Problems of Quantum Physics

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1. Quantum theory vs. hidden variables

The question of hidden variables underlying the quantum statistics is not as straightforward as it might seem. Most people think the issue has been resolved by Bell's theorem and the experiments designed to test for the existence of local hidden variables. Apart from important qualifications to the straightforward interpretation of these results pointed out by Selleri and others, there are several more or less physically plausible theories of quantum phenomena that introduce hidden variables of one sort or another that are not tested by these results. These are the so-called 'collapse' theories, like the Ghirardi-Rimini-Weber-Pearle theory or the Bohm-Bub theory, and 'non-collapse' theories, like the 'empty-wave' modifications of the de Broglie-Bohm theory, that have testable consequences differing from quantum mechanics. The Bohm-Bub theory predicts that sequences of 'collapse' processes, as might occur in quantum measurements or in the decay of a fundamental particle, will yield a different statistics from the quantum statistics if the time interval between 'collapse' processes is sufficiently small (estimated as of the order of 10^{-13} sec). Experiments that are in principle possible have been suggested for 'empty wave' theories (see "Empty Wave Detecting Experiments: A Comment on Auxiliary 'Hidden' Assumptions", by Ron Folman and Zeev Vager, *Foundations of Physics Letters* **8**, 55-61 (1995)), and it is not too far-fetched to suppose that an experimental test might be on the horizon for the Ghirardi-Rimini-Weber-Pearle theory, as well.

2. Most important unresolved issue in quantum physics today

In my opinion, the most important unresolved issue in quantum physics today is the measurement problem, which is a problem of interpretation.

One might wonder why, and in what sense, a fundamental theory of how physical systems move and change requires an interpretation. Quantum mechanics is an irreducibly statistical theory: there are no states of a quantum mechanical system in which all dynamical variables have determinate or 'sharp' values—no states that are 'dispersion-free' for all dynamical variables. Moreover, the so-called 'no-go' theorems exclude the possibility of defining new states in terms of hidden variables, in which all dynamical variables—or even certain well-chosen finite sets of dynamical variables—have determinate values, if we assume that the values assigned to related dynamical variables by the new hidden variable states are subject to certain constraints, and we require that the quantum statistics can be recovered by averaging over these states. So it is standard practice to refer agnostically to 'observables' rather than dynamical variables (which suggest determinate values evolving in time), and to understand quantum mechanics as providing probabilities for the outcomes of measurements of observables under physically well-defined conditions.

This neutrality only goes so far. All standard treatments of quantum mechanics take an observable as having a determinate value if the quantum state is an eigenstate of that observable. This principle is explicitly endorsed by Dirac (*The Principles of Quantum Mechanics*, fourth edition, Oxford, 1958, pp. 46-7) and von Neumann (*Mathematical Foundations of Quantum Mechanics*, Princeton, 1955, p. 253), and clearly identified as the 'usual' view by Einstein, Podolsky and Rosen in their classic 1935 argument for the incompleteness of quantum mechanics. Since the dynamics of quantum mechanics described by Schrödinger's time-dependent equation of motion is linear, it follows immediately from this orthodox interpretation principle that, after an interaction between two quantum mechanical systems that can be interpreted as a measurement by one system on the other, the state of the composite system is not an eigenstate of the observable measured in the interaction, and not an eigenstate of the indicator observable functioning as a 'pointer.' So, on the orthodox interpretation, neither the measured observable nor the pointer reading have determinate values, after a suitable interaction that correlates pointer readings with values of the measured observable. This is the measurement problem of quantum mechanics.

There are three possible ways of resolving the measurement problem. Either we change the linear dynamics of the theory, or we change the orthodox interpretation principle, or we adopt what Bell has termed a 'fapp' ('for all practical purposes') solution.

The Bohm-Bub theory alters the linear dynamics by adding a non-linear term to the Schrödinger equation that effectively 'collapses' or projects the state onto an eigenstate of the pointer-reading and measured observable in the pointing process. Currently, the Ghirardi-Rimini-Weber-Pearle theory is a much more sophisticated proposal along these lines. 'Fapp' solutions range from the Daneri-Loinger-Prosperi quantum ergodic theory of macrosystems to the currently fashionable 'decoherence' theories (proposed by Zurek and others). Essentially, the idea here is that the system and measuring instrument are always interacting with the environment, and that an infinitesimally small time after a measurement interaction, the state of the system + measuring instrument is, for all practical purposes, indistinguishable from a state in which the measured observable and pointer reading have determinate values. The information required to distinguish these two states is almost immediately irretrievably lost in the thermodynamic degrees of freedom of the environment.

The remaining possibility is to adopt an alternative principle for selecting the set of observables that have determinate values in a given quantum state. This was Bohm's approach, and also—very differently—Bohr's. Bohm's hidden variable theory or 'causal' interpretation takes the position of a system in configuration space as determinate in every quantum state. Certain other observables inherit determinate status at a given time from this 'preferred' always-determinate observable and the state at that time. For Bohr, an observable can be said to have a determinate value only in the context of a specific, classically describable experimental arrangement suitable for measuring the observable. Since the experimental arrangements suitable for locating a quantum system in space and time, and for the determination of momentum-energy values, turn out to be mutually exclusive, there is no unique description of the system in terms of determinate properties associated with determinate values of certain observables. So which observables have determinate values is settled pragmatically by what we choose to observe, *via* the classically described measuring instruments we employ, and is not defined by the system alone. Bohr terms the relation between space-time and momentum-energy concepts 'complementary,' since both sets of concepts are required to be mutually applicable for the specification of the classical state of a system.

What is generally regarded as the 'Copenhagen interpretation' is some fairly loose synthesis of Bohr's complementarity interpretation and Heisenberg's ideas on the significance of the uncertainty principle. It is usual to pay lip service to the Copenhagen interpretation as the 'orthodox' interpretation of quantum mechanics, but the interpretative principle behind complementarity is very different from the Dirac-von Neumann principle. Unlike Dirac and von Neumann, Bohr never treated a measurement as an interaction between two quantum systems, and hence had no need for a special 'projection postulate' to replace the linear Schrödinger evolution of the quantum state during a measurement process. Both Dirac and von Neumann introduce such a postulate to describe the stochastic projection or 'collapse' of the state onto an eigenstate of the pointer reading and measured observable—a state in which these observables are determinate on their interpretation. (See Dirac, *op. cit.*, p. 36 and von Neumann, *op. cit.*, p. 351 and pp. 417-418.) The complementarity interpretation avoids the measurement problem by selecting as determinate an observable associated with an individual quantum 'phenomenon' manifested in a measurement interaction involving a specific classically describable experimental arrangement. Certain other observables, regarded as measured in the interaction, inherit determinate status from this pointer observable and the quantum state.

Einstein viewed the Copenhagen as 'a gentle pillow for the true believer.' For Einstein, a physical system has a 'being-thus,' a 'state of reality' that is independent of other systems or means of observation. He argued that realism about physical systems in this sense is incompatible with the assumption that the state descriptions of quantum mechanics are complete. What Bell's theorem shows, extending Einstein's arguments, is that certain sorts of 'completions' of quantum mechanics are ruled out. This is an important result, but it does not rule out all possible completions of quantum mechanics. Resolving the measurement problem without changing the linear dynamics of the theory would require characterizing the possible completions of quantum mechanics that are not ruled out by Bell's theory or other 'no-go' theorems. In my view, it is only within the framework of some such 'completion' of quantum mechanics that we have the possibility of a coherent interpretation of the theory that resolves the measurement problem. Without a resolution of this issue, quantum mechanics can only have the status of a remarkably accurate predictive tool: we have no clear understanding of how the universe can possibly be like quantum mechanics says it is.

3. The earlier debate (Solvay 1927)

The current foundational debate deals with substantially the same issues that engaged Bohr and Einstein, but there have been major advances in clarifying the nature of these problems. Perhaps the most important advances concern 'no-go' theorems for hidden variables (Kochen and Specker; Bell; Greenberger, Horne and Zeilinger; Kochen and Conway, Mermin, Peres, Penrose, Kernaghan and others), which considerably limit the possibilities for an interpretation of quantum mechanics satisfying the broad realist requirements of Einstein. A variety of rival interpretations of the theory have now been developed quite extensively (e.g. Bohm's 'causal' interpretation, the modal interpretation), so general foundational questions are now addressed n the context of precisely articulated alternative views.

4. Future developments of foundations

I think the most likely development in the foundations of quantum mechanics in the near future can be expected in the area of quantum computers and quantum cryptography. There are interesting theoretical results in this area, with hints of possible physical realizations. I think the measurement problem will simmer for a while yet before leading to any real change in physics.

Fundamental Problems of Quantum Physics

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1. Quantum theory vs. hidden variables

The confrontation between these two viewpoints has been resolved in the sense that, in my opinion, local hidden variable theories are definitely ruled out. I know, of course, of the various proposals that were made in attempts at salvaging realism and locality by referring either to some remaining experimental uncertainties or to the idea of a purely wave-like theory of light, *etc.*, and I consider all of them as being too artificial to be credible. On the other hand, *nonlocal* hidden variable theories are not ruled out by experiment. My objection to them is therefore very much weaker. It is significant nevertheless. To put it in a nutshell, they are intricate, more than one in number, incompatible with special relativity and, above all, useless for prediction: which means, in fact, not only that they do not contribute to improving our predictive recipes, but even that they are not needed for scientifically describing the *phenomena* (collective appearances). I view them, therefore, as "brilliant metaphysics".

2. Most important unresolved issue in quantum physics today

The issue is to try and convince our fellow physicists—and the laymen as well!—that, to use Bohm's words, the "implicit order" of Reality must be immensely different from the "explicit order," which is the order both science and commonsense describe. Because of nonseparability, *etc.*, these two orders are so different indeed that the world we live in (corresponding to explicit order) is but a world of appearances, as Plato guessed. The difference between Plato's time and ours is that his theory was merely a nice, provocative guess, whereas a strong argument is now available in favor of the truth of the myth of the cave: namely, the substance of my answer to Question 1 combined with the fact that conventional quantum mechanics—the only firmly grounded theory we have—cannot be interpreted as describing Reality.

3. The earlier debate (Solvay 1927)

In substance the present debate is almost the same one as the one that took place between the objectivist realists—such as Louis de Broglie and Einstein—on the one hand and the people directly or indirectly (unconsciously perhaps) inspired by Kant—such as Bohr, Heisenberg and Schrödinger—on the other hand. Today as then, the objectivist realists cannot even imagine that, in the 20th century, after all the scientific discoveries that were made, the myth of the cave can still be taken seriously by some. Today as then, their opponents cannot understand how it is possible not to realize that *all* our perceptions and the totality of our thinking are unavoidably shaped by our senses and our common mental structure. The only significant difference between now and the early 20th century is that (due presumably to differences in education) present-day physicists are considerably less informed than the physicists of that time about basic issues in philosophy.

4. Future developments of foundations

The teen-ager's education in classical philosophy will presumably remain more or less in the state in which it now is, so that the physicists of the new generations will begin their career with the same "commonsense" prejudices as their elders. Faced with quantum mechanics, they will, therefore, take up the same old problems and riddles over again, and there is a nonnegligible probability that a flow of intelligent but hardly conclusive models will go on being produced. It may of course be hoped that this will eventually lead to some breakthrough comparable to the Bell theorem, but such events are essentially unpredictable.

Concerning the distant future, perhaps a theory relating consciousness with quantum mechanics will, in the end, be produced. But, mind you, what I expect will come out is not a quantum theory of consciousness that would, in some sense, "reduce mind to matter." In fact, I cannot dissociate my expectations in this field from my own overall theory, which is that empirical reality and consciousness a-temporally generate one another within independent Reality (*i.e.*, the ultimate "stuff"). This is terribly vague and it would be nice if it got more precise, a condition being that the theory should account for—or at least not be incompatible with—the unity of the self (*i.e.*, the fact that the word "I" is meaningful for humans and, as it seems, for animals: for the physicist this is, I think, presently a mystery).

Further reading

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Fundamental Problems of Quantum Physics

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1. Quantum theory vs. hidden variables

The experiments performed in the 70's and early 80's are not conclusive. In spite of this, they are considered, by several people, crucial experiments in favour of existing quantum theory. The History of Science teaches us to be careful with the idea of crucial experiments. In the 19th century Fizeau and Foucault performed, independently, "crucial" experiments and concluded that *light is a wave, and consequently, Newton's corpuscular theory of light was wrong*. Evidently, the Fizeau and Foucault experiments are not crucial ones to decide about duality. As another example, the Michelson-Morley experiment cannot be considered as crucial to discard the existence of the *ether*.

Concerning the experiments performed in the 70's and early 80's on quantum nature, we can say that:

1. The original Bell's inequality (weak) has not been violated.
2. The above experiments violate the strong Bell inequalities. These inequalities are concluded with the help of *additional assumptions*. Besides this, very low efficiency detectors are used in these experiments. What do these experiments refute? *Locality or additional assumptions?*
3. Therefore, it is strongly recommended that new types of experiments be performed without the adoption of such assumptions.
4. Several possibilities exist. The proposal of Privetera and Selleri on the decay of a vector meson into a pair of neutral kaons constitutes one possibility for the near future. In order to perform these experiments *no additional assumptions are required*. Besides this, the efficiency of the detectors is very high (~ 100%).
5. Another point to be taken into account concerns the explanatory power of local realistic models. For example, I have been able to explain Aspect's experiment on the basis of local hidden variable models which agree with the predictions of quantum mechanics for *all* measurable quantities. So, local realistic models have good explanatory power.

2. Most important unresolved issue in quantum physics today

Scientists have ascribed many different meanings to influential ideas. In consequence of this, a great deal of confusion took place in the quantum debate. *Complementarity* and *completeness* are outstanding examples. Several of the meanings ascribed to these words have nothing to do with Bohr's original concepts. Bohr's original complementarity constitutes the claim that it is impossible to have *space-time* and *causal* descriptions of atomic phenomena simultaneously. Following Bohr, space-time and causality are necessary parts of the classical tradition, but they are mutually exclusive. They are complementary. The original Bohr complementarity has to do with the von Neumann impossibility proof forbidding causal completion of quantum mechanics. However, the impossibility proofs forbidding causal completion of quantum mechanics were entirely overcome. In this direction, Bohm, Bell, Selleri and others have provided some convincing examples. In fact, we are able to do what complementarity forbids. Today, the *completeness* problem is not the most important one. With the historical development of the quantum debate it becomes a secondary problem. In spite of this, *complementarity* and *completeness* survive with different meanings. For example, the idea that knowledge is necessarily incomplete and consequently requires a complementary part or a complementary approach is commonly attributed to Bohr. However, this meaning does not constitute a singular property of human mechanics because it applies to any field of knowledge. As another example, Prigogine argues that the present quantum mechanics is not a complete one; however, his concept of completeness is substantially different from the concept of completeness involved in the original Einstein-Bohr debate. Prigogine claims that the present quantum mechanics is not a complete theory by virtue of the fact that *time* in it is merely a parameter. To him, *time* in quantum mechanics is not a physical magnitude. In the mathematical formalism there are hermitian operators associated with, respectively, linear momentum, position, energy, *etc.*, but there is no hermitian operator associated with *time*. Besides this, *time* in quantum mechanics has nothing to do with *irreversibility*. Consequently, *time* in quantum mechanics does not produce *becoming*. The present quantum mechanics, unlike statistical thermodynamics, is a science of *being*. He considers that the future quantum mechanics will be a science of *becoming* in which the fundamental irreversibility will be incorporated. Perhaps Prigogine's program is a good direction for future developments. However, recent two-photon interference experiments, for example, do not involve *becoming* in the Prigoginian sense. In these experiments there is irreversibility because quantum objects are destroyed, while measurements are performed, but not in the sense of Prigoginian *becoming*.

I think that there are at least two major problems in quantum theory. They are the *locality* problem and the *contradiction* (or perhaps incommensurability in the Kuhnian sense) *between quantum and relativity theories*. All the fields of Natural Philosophy are in agreement with Local Realism. Present quantum theory constitutes the only exception. The lack of a suitable and acceptable solution for the locality problem inhibits future developments.

3. The earlier debate (Solvay 1927)

The quantum mechanical debate has a very intricate history. Since 1927 at the Solvay conference, many different aspects of this matter have been pointed out. We can say *grosso modo* that the debate began with the *completeness* problem, and later evolved into the *locality* debate. The debate, however, is replete with misunderstandings. For example, regarding the *completeness* problem, the dominant opinion that Bohr was the winner and Einstein the loser is absolutely false. I think that the present development of quantum theory indicates that Einstein was *right* in his criticism against Bohr, *i.e.*, the quantum theory that existed in 1927 was not a complete one. The arguments in favour of this are the following:

1. If one considers that the apparatus performing measurements on the quantum system is a classical entity (quantum mechanics in 1927), then this implies *instantaneous action at a distance*. The quantum system here can be a pair of particles described by a singlet state.
2. If one considers that the apparatus performing measurements on the quantum system is a quantum entity, then this implies both: *instantaneous action at a distance and non-conservation of physical quantities*.
3. If one considers a different measurement theory like the *imperfect measurements* of Wigner, Araki and Yanase (proposed in the 60's) then both the implications in point 2. are avoided. However, Bell's inequality continues to be violated.
4. The above considerations do not resolve the locality problem, but indicate that the improved quantum theory proposed in the 60's *has changed the quantum theory of 1927. So, the quantum mechanics of 1927 is not a complete one, and consequently, Einstein was right*. With the improved quantum mechanics of Wigner, Araki and Yanase and with other developments, *nonlocality* becomes a very strange property: *it is not action at a distance; it is not persistence of pre-existing correlations; it does not involve energy propagation in space, etc.* So what, if anything, is *nonlocality*? I think that nobody knows. If anybody really knows, he (or she) has not explained it in a clear way.

4. Future developments of foundations

We can say that the quantum and relativistic programs are very different. This incommensurability has probably to do with the locality problem. In order to see an example, we can say that the General Theory of Relativity (GTR) presents a good explanatory power to describe the observed decrease of the period of pulsar PSR 1913 + 16. The observed decrease is $(2.40 \pm 0.09)\ 10^{-12}$ s s^{-1}. According to the GTR, this decrease is ascribed to the emission of gravitational waves at the rate of $(2.403 \pm 0.02)\ 10^{-12}$ s s^{-1}. The agreement between GTR and the observational data is stupendous.

An interesting point is that GTR is a local realistic theory. In fact, GTR is entirely compatible with realistic philosophy, and besides, obeys the Einstein separability or locality principle. For example, gravitational waves do not involve instantaneous action at a distance. These actions are transmitted through a space-time from point to point and from instant to instant. The comparison between this situation and the corresponding one described by the singlet state in quantum mechanics is very uncomfortable: a theory whose explanatory power applies to enormous distances is *local*, while another initially built for the atomic range is *nonlocal*. In fact, quantum and relativistic theories are philosophically different. If we believe that a rational reconciliation is possible, an improved quantum relativistic theory must be formulated. It is possible that the *locality* problem is the root of this difficulty.

On the Future Course of Quantum Physics

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1. Most important unresolved issues in quantum physics today

What are the most important unsolved issues of Quantum Mechanics? In my view, there are two crucial problems to be solved: 1) the problem of 'wave-particle dualism' and 2) the problem of fusing the theory of relativity with the quantum theory.

The Problem of Wave-Particle Dualism

The situation is as follows: It is claimed that under particular sorts of experimental conditions, elementary particles, such as electrons, behave as though they were discrete particles, while under other sorts of conditions they behave as though they were continuous waves. Consider, for example, the Young double slit experiment. A beam of electrons impinges upon a screen, S_1, that has two slits open. If the width of the slits is sufficiently small, of the order of the electron's de Broglie wavelength (given that it is a single energy beam), $l = h/p$, where h is Planck's constant and p is the electron momentum, then a diffraction pattern should be seen on a second screen S_2 a distance beyond S_1 and parallel to it.

On the other hand, if only one of the slits in S_1 is open to the impinging monochromatic electron beam, one should see an image of the open slit on S_2—indicating that under the latter circumstance, the 'electrons' are (almost) discrete. By adjusting the slit width , one may approach an image of the electron beam on S_2 that is truly discrete. But it is important that from the empirical side, this limit cannot be achieved! However, the conclusion usually reached is that under the latter condition, one does indeed see a discrete particle of matter.

The former case, where the two slits are open to the electron beam, is physically equivalent to the observation of electron scattering from a crystal lattice, where the spacing between atoms of the lattice is the order of magnitude of l. In this case (the experimentation of Davisson and Germer, and G.P. Thomson), one observes a diffraction pattern on an electron absorbing screen a distance away from the crystal. The conclusion is then reached that if one should observe an electron beam under the experimental conditions where one would look for wave properties, such as the 'interference bands' of a diffraction pattern, then this is what the electrons would be at that instant. But if one should do an experiment designed to look for the particle-like properties of the electrons, this is what they would be under those conditions.

The latter model in terms of 'wave-particle duality' would clearly be unacceptable as an interpretation if one should assume an ontology for the electron that is independent of any measurement. In this case, one would say that the *real* electron is either a discrete particle, localized in space, or a continuous wave (that is not generally localized at a particular place in space, except for its peak). But the real electron could not be both a continuous wave and a discrete particle, simultaneously, even though it may look like one or the other under differing circumstances of observation. Such a view would be consistent with the epistemological approach of realism.

To explain 'wave-particle dualism,' Bohr proposed a different epistemological view—that of logical positivism. Here it is said that the true electron may be understood in terms of logically exclusive assertions, so long as each of these is determined by a measurer at different times, under different experimental conditions. This view led Bohr to generalize the pluralistic approach to matter of 'wave-particle dualism' to his principle of complementarity, as foundational in nature—a pluralistic view.

At this stage, one must ask the question: Is the Bohr philosophy of complementarity really necessitated by the empirical facts about electrons (or other elementary particles of matter or radiation)? To answer this question, consider once again the Young double slit experiment. It is clear that when both slits in S_1 are open to the impinging electron beam, the empirical evidence is that a diffraction pattern is produced on the second screen S_2. This reveals clearly the electron's wave-like nature—the matter waves discovered by Louis de Broglie. But if only one slit is open in S_1 does one really detect the absorption of a single, discrete electron on S_2? The answer is no. Firstly, one never sees an infinitely sharp image of the slit of on S_2. It is always a diffuse image, empirically. Though the quantity of diffusivity about the central image may be greatly reduced, it cannot be reduced to zero!

Secondly, a close examination of the diffuse image of the single open slit in S_1 created by electrons passing through it to S_2 would reveal a diffraction pattern within it, with interference maxima and minima—no matter how close the diffuse image is to discreteness! Similarly, all other experiments on the observations of elementary particles reveal a finite spread, rather than discreteness. The experimenter can never totally eliminate the diffusivity!

The reply to this experimental fact, by those who believe in the reality of the 'particle aspect' of wave-particle dualism is this: Indeed there is a discrete point particle there, but when it interacts with the measuring apparatus (the screens S_1 and S_2 in this case) it disturbs the observer, thereby yielding an interference pattern due to the combination of the wave components of a packet, created by the interaction with the apparatus, causing the single wavelength electron to disperse into many other wavelength possibilities. This irreducible 'fuzziness' is 'explained' in terms of the 'Heisenberg uncertainty principle,' applied to the motion of the supposed discrete electron, with an initial single wavelength.

Still, the empirical facts do not attest to the existence of a localized, discrete electron, under any conditions. It is my conclusion, then, that the empirical facts compel one to reduce 'wave-particle dualism' to 'wave monism.'

The theoretical difficulties encountered in this problem are then due to the supposition of a particulate model of matter—that any macroscopic quantity of matter must be composed of a large number of 'atoms' of matter—be they electrons, protons, neutrons, complex atoms, quarks or molecules. This is a model of matter assumed in various forms since ancient Greece. But along with this historical sequence of the atomistic models of matter, there has been lurking in the foreground a continuum model of matter, whereby the 'atoms' are truly illusory. In the latter view, the seemingly localized atomic constituents of matter are actually distinguishable modes of a continuum, rather than separable things. The latter continuum view is indeed more abstract than the atomistic model, though not necessarily a false view, in spite of our perceptions of the world in terms of things.

Summing up, the very important empirical discoveries of the 20th century, that both electromagnetic radiation (*e.g.* photons) and matter (*e.g.* electrons) have definite continuum wave qualities under particular experimental conditions that are designed to detect wave features and (seemingly) localized particle qualities under other sorts of experimental conditions that are designed to look for particle-like qualities led to the philosophical revolution in physics that was instigated by Bohr and Heisenberg—a pluralistic view based on the epistemology of logical positivism. But this 'new view' was indeed not necessary because the particle aspect of 'wave-particle dualism' is not directly observed; it is rather a model-dependent conclusion. The actual experimental observations of matter and radiation in the microdomain, however, compel the continuous wave view.

The way in which the followers of the atomistic model of matter interpret the observed irreducible wave nature of their 'particle' is to introduce the continuous field of probability. The laws of the matter waves, as named by de Broglie, then become a probability calculus. The solutions of these laws, called 'quantum mechanics,' then relate to continuously varying probabilities in space and time that underlie the measurements (necessarily by a macroapparatus) of the physical properties of the elements of micromatter. This is a more general sort of probability calculus than classical probability theory because it not only entails the probabilities of finding the elements of matter in one state or another, it also entails the probabilities of transitions between all of the possible states of a material system.

Following this probability wave theory further, regarding the 'particle ontology', it follows that there are *canonical variables* of a particle of matter, in pairs, such as position/momentum, energy/time or angular momentum/its orientation, that obey uncertainty relations. It is predicted that, for example, the more accurately that one can measure the position x of a particle, the less accurately can one determine the simultaneous value of its momentum in this direction, p_x The uncertainties in these measurements, Δx and Δp_x are restricted according to the Heisenberg inequality $\Delta x \cdot \Delta p_x \geq h/2p$, where h is the fundamental constant that is 'Planck's constant.' This is called the 'Heisenberg uncertainty relation.' Its derivation depends on the 'linearity' of the probability calculus that is quantum mechanics, and its necessarily imposed 'principle of linear superposition' in accordance with the rules of probabilities.

Richard Feynman made the following comment in regard to the Heisenberg uncertainty relations vis a vis quantum mechanics:*

> *The uncertainty principle "protects" quantum mechanics. Heisenberg recognized that if it were possible to measure the momentum and the position simultaneously with greater accuracy, the quantum mechanics would collapse. So he proposed that it must be impossible. Then people sat down and tried to figure out a way to measure the position and the momentum of anything—a screen, an electron, a billiard ball, anything—with any greater accuracy. Quantum Mechanics maintains its perilous but accurate existence.*

There are two troubles with Feynman' s statement. One is that he tacitly assumes that what it is that is real is exhausted by what one can measure. Why is this necessarily so? It may be that there are many physical features of elementary matter that are not directly measurable, yet that would have indirect consequences in physical measurements. But the latter view would be inadmissible by the epistemological view of logical positivism—a philosophy that Feynman and Heisenberg assume at the outset. The former view is one of realism—the idea that there are indeed features of matter that are not directly measurable by us, yet that can be deduced from the correct set of hypotheses regarding its nature. Indeed, Feynman and Heisenberg's view is in agreement with the ancient edict of Protagoras in Greece, that 'man is the measure of all things'. But it is certainly in disagreement

* R.P. Feynman, R.B. Leighton and N. Sands, *The Feynman Lectures in Physics* (Addison Wesley, l963), Chapter 37.

with the Platonic view that our observations are merely 'shadows on the wall,' projected there by a real world, that we are obligated to probe, if we are to gain any true comprehension of the world.

The second error in Feynman's statement is that he assumes at the outset that, fundamentally, the material world is composed of 'things'—discrete, localized, separable entities, with intrinsic values for their momenta, positions, and all other localized properties that classify them as individuated entities. Yet, the latter is certainly not, necessarily, an absolute truth of nature! It is based on a particular model, that of atomism. he continuum model, that I will discuss below is the view that is implied by the theory of general relativity.

2. Future developments of foundations

The preceding discussion brings us to a resolution of the problem of matter in terms of a fundamental continuum. In this case, 'wave-particle dualism' is replaced by 'wave monism,' as a genuine paradigm shift. There is no problem in this context to 'explain' the wave nature of micromatter, such as the electron, because it is in fundamental terms only a wave!

If matter is to be represented by a purely continuum field in spacetime, and if this is not a probability wave for a particle at the outset, as quantum mechanics advocates, then what physical feature of matter does this 'wave' represent? That is to say, if quantum mechanics is a low energy, linear approximation for a general theory of matter, what is the correct interpretation of this theory?

It has been my contention that quantum mechanics is a low energy, linear approximation for a field theory of inertia, whose conceptual and mathematical structure are rooted in the theory of general relativity. The general form of this theory is that it is 1) nonlocal, 2) nonlinear and 3) a continuum, singularity-free field theory.

The theory is 'nonlocal' because it does not describe any individual trajectories in spacetime, anywhere. It is 'nonlinear' for two essential reasons. First, the laws of motion are nonlinear because they represent components within a closed system from the outset. This arises as follows: Consider the material components A and B of a closed system, such as the ripples of a pond. Ripple A exerts a force on ripple B, causing B to move in a particular way in the pond. The reaction of A to B, in turn, causes a change in A's original motion, which in turn changes B's motion. Thus, the motion of B affects itself, by virtue of its interaction with A. In expressing the law of motion of the component of the pond, B, one then sees that it is a differential equation, whose solution is the field of motion of B, but whose operator also depends on the solution for B's motion. This equation is then 'nonlinear, since it depends on the solution for B's motion to a higher power than unity.

The second reason for the necessary appearance of nonlinearity in the laws of matter in the context of general relativity is that all fields in this theory must be mapped in a curved spacetime. The curvature is a consequence of the existence of matter, anywhere. The linear limit of the equations then corresponds to the depletion of all matter, everywhere—the vacuum state. The latter, which corresponds with the special relativity metric, is then an approximation that assumes that the material system is sufficiently rarefied to allow the use of a flat spacetime and Euclidean geometry. But the general system, without approximation, is necessarily nonlinear—this is equivalent to the statement that one may not exclude 'gravitation' in the laws of matter, except as some sort of approximation, since this manifestation of interacting matter is a direct expression of the curvature of a nonlinear spacetime.

As we have discussed above, quantum mechanics is a form of a probability calculus. Because of the rules that must be obeyed by probabilities, quantum mechanics must then entail, in principle, the requirement of linear superposition. Quantum mechanics is then, necessarily in terms of linear differential equations. These are in the form of 'eigenvalue equations' for each measurable physical property of a quantity of elementary matter, wherein the solutions of these equations are the 'eigenfunctions,' each representing the state of the system to be measured, and interpreted as a 'probability amplitude,' The particular 'eigenvalues' in this equation, in turn, are the measured values of the physical properties that are associated with these eigenfunctions. If we call the linear operators of this type of equation O, then their eigenfunctions may be labeled y_n and their eigenvalues l_n.

If O_1 and O_2 are two such linear operators that correspond to the measurements of two different sorts of physical property, and if they do not commute, *i.e.* if $O_1O_2 - O_2O_1 \neq 0$, it then follows that one cannot prescribe the properties '1' and '2' simultaneously for this micromatter. For example, if O_1 is the operator that represents the measure of the position x of a particle from the origin and O_2 represents the measure of its momentum in the x-direction, simultaneously, p_x, then the operators O_1 and O_2 do not commute. It then follows that the root-mean square value for the measurement of the electron's position, Δx and than of its momentum (in the x-direction) Δp_x obey the Heisenberg uncertainty relation $\Delta x \Delta p_x \geq h/2p$. The derivation of these relations from the eigenfunction formalism of quantum mechanics is dependent on its linearity, because of the use of the Fourier theorem to derive it.

If the laws of matter, in their exact form, are nonlinear rather than linear, the feature of linear superposition cannot be true, and these laws cannot then be in the form of a probability calculus. The Heisenberg uncertainty relations then do not follow as a general law of matter - in spite of the claim of most followers of the Copenhagen school that these uncertainty relations are a necessary truth of nature! Nevertheless, the mathematical form of quantum mechanics has been eminently successful in its accurately representing the low energy empirical data of micromatter nonrelativistically—molecular, atomic, nuclear and particle physics, at least phenomenologically. Thus, the field theory of matter that is to *explain* the nature of matter in the micro-domain must be a nonlinear field theory for a closed system, whose low energy, linear approximation, is precisely the probability calculus that is the formal structure of quantum mechanics in the nonrelativistic limit.

It is the latter generally covariant field theory of matter that is the underlying field theory of inertia that resolves the dilemma of wave-particle dualism. This is so because with this view, the particle aspects of this dualism are truly 'exorcised'— leaving us with a purely continuum theory of matter.

General Relativity as a Theory of Matter

Einstein anticipated that a true unified theory in general relativity must yield a formal expression of quantum mechanics, in some limiting approximation. I have found in my research program that the essential ingredient to unify the forces of nature is to take account of not only the field unification of the physical forces exerted by matter on other matter in terms of the general manifestations appearing as one sort of force or another under corresponding conditions of observation, but it must also include the dynamical basis of the reaction of the interacting components, which in turn necessitates the inclusion of the inertial manifestation of matter. This is in the full spirit of Newton's third law of motion, which I regard as a very important precursor for Einstein's theory of general relativity. I have argued that the latter unification with a field theory of inertia must necessarily yield the formal structure of quantum mechanics, as a linear approximation. This is similar to Einstein's theory of general relativity superseding Newton's theory of universal gravitation, both in terms of its conceptual and mathematical content. Yet, the equations of Newton's theory of gravity serve a useful purpose as they are a good mathematical approximation for Einstein's equations, in particular limits.

With this approach in mind, then, Einstein's intuition would be fulfilled wherein the Hilbert space probability calculus, that is quantum mechanics, emerges as a linear approximation for a continuum field theory of inertia in general relativity. This theory is 1) nonlocal, 2) nonlinear and 3) deterministic—all features that are inconsistent with the mathematical requirements of conceptual bases of the quantum theory. The underlying explanation for the quantum mechanical predictions of features of micromatter must then be in terms of a field theory of inertia of matter, in general relativity.

The continuum feature of general relativity, as a theory of matter, follows from the underlying symmetry group—a group of continuous, analytic spacetime transformations, such that the forms of the laws of nature are preserved—this requirement is called "general covariance," which is the basic axiom of Einstein's theory.

The primary reason that the spacetime transformations must be analytic (as well as continuous), that is, requiring that these transformations have derivatives of all orders at all points of spacetime, is that this is a necessary and sufficient requirement for the existence of conservation laws in the local, flat spacetime limit (conservation of energy, momentum and angular momentum). The symmetry group of general relativity is then a *Lie group*, characterized by 16 essential parameters—the 16 derivatives $(¶x'^{m}/¶x^{n})$ [m,n = 0, 1, 2, 3 denote the time coordinate ('O') and the three spatial coordinates of one (primed) reference frame with respect to the other (unprimed) one]. The implication here is that the laws of nature must be nonsingular everywhere—such functions are called "regular." The latter requirement follows from Noether's theorem.

The foregoing discussion relates to one of the three essential axioms that underlie the theory of general relativity, the axiom of "general covariance" also called the "principle of relativity." The other two axioms of the theory of general relativity that must incorporate the quantum theory as a linear approximation are 1) the correspondence principle and 2) the generalized Mach principle. An example of the principle of correspondence was discussed above, in the requirement that the new theory, based on a new paradigm, must have a mathematical form that smoothly approaches the form of the older theory, as Einstein's field equations for gravity approach the form of Newton's equation for universal gravitation. Other examples are Bohr's principle of correspondence, requiring that the quantum mechanical formalism must approach the classical Newtonian theory of particles, in the limit when quantities of mechanical action become large compared with Planck's constant *h*. And, of course, the example cited in this author's work in which the generally covariant, nonlinear, nonlocal theory of inertia smoothly approaches the linear form of quantum mechanics, in the low energy limit in the microdomain, demonstrates the principle.

The third underlying axiom, the generalized Mach principle, asserts that not only the inertial mass, but all alleged intrinsic properties of matter (such as electric charge, magnetic moment, *etc.*) also become measures of coupling within an assumed closed system. This view then disposes of all remnants of the atomistic model of matter. It leads us to a fully holistic understanding of the material world, in any of its domains—from fermis (and less) to light-years (and greater).

It is my opinion that the latter view, which fully exploits the conceptual approach of Einstein's theory of general relativity in a theory of matter, is the understanding that present views in physics, including quantum theory, will evolve to in the future. I feel that such a paradigm shift will likely be in place by the middle of the 21st century.

I do not claim that this understanding of the material world will be a completion of our understanding in physics. But I do feel that it is in the correct direction toward *increased* understanding. Indeed, this is all that a scientist should strive for, in my view.

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Foundations of Quantum Physics: Present and Future

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1. Quantum theory vs. hidden variables

Following Bell [1], "local hidden variable" (LHV) theories may be defined by the condition that every correlation predicted by the theory could be written using Bell's formula (Eq. (2) of Ref. [1]). The dominant view among physicists is that LHV theories are not possible, and there are two apparently strong arguments for this belief:

1. Bell's theorem proves that no LHV theory can agree with quantum mechanics (QM) for all possible experiments (see Ref. [2]). But QM has been so spectacularly confirmed that its eventual failure appears as extremely implausible. This fact excludes, *via* Bell's theorem, the possibility of LHV theories, even without the need for new experiments.
2. Violations of Bell's inequalities have been reported in several experiments, *e.g.* those performed by Aspect *et al.* [3]. As the Bell inequalities are necessary conditions for the existence of a LHV theory, the experiment refutes all LHV theories.

I shall analyze these arguments, beginning with the second one.

1a. Have local hidden variables been refuted by experiments?

All experts in the field know that no uncontroversial empirical violation of a Bell inequality has yet been produced, because all experiments performed to date suffer from loopholes [4]. However, the received wisdom is that these loopholes are almost irrelevant. I shall reproduce here the current argument for this irrelevance with reference to the Aspect experiments [3], which are widely accepted as the most reliable tests of LHV theories performed thus far. In these experiments, an atom emits two photons within a short time interval. Each one of these photons may eventually enter a lens system, through some aperture, cross a polarizer and be detected at a photomultiplier. In this way, the polarization correlation of the emitted photons may be measured and the value of this correlation as a function of the polarizer positions may, in principle, discriminate between QM and LHV.

The Bell inequality states that a certain combination of probabilities (of single and coincidence detection counts) is non-negative. The inequality should be fulfilled in any LHV theory, whatever the ensemble for which the probabilities are defined. We may consider, from the full ensemble of photon pairs emitted by the atoms, the subensemble of pairs such that both photons enter the apertures, and define Bell inequalities on this "passed subensemble." If we were using two-channel polarizers, as in the second Aspect experiment [3], and 100% efficient detectors, all pairs in the "passed subensemble" would be detected. In these conditions, it is known that quantum predictions violate a Bell inequality and no escape seems possible: either QM or the whole family of LHV theories would be refuted by the Aspect experiments, if any were made with high-efficiency detectors. In practice, detectors with the required efficiency are not yet available and a loophole exists due to this fact. Therefore, LHV theories may exist giving predictions in agreement with both QM and the experiment for low efficiency, but departing from QM in the high efficiency domain, never violating a Bell inequality. However, the possibility that nature behaves in such a "conspiratorial" manner has been considered unbelievable. For instance, Bell wrote: "It is hard for me to believe that quantum mechanics works so nicely for inefficient practical setups and is yet going to fail badly when sufficient refinements are made" [5]. This opinion is shared by the main part of the physics community.

Something is wrong with the above argument, however. In fact, a LHV model has been found [4] which gives predictions for the Aspect experiments that are in perfect agreement with QM *even assuming ideal setups, in particular 100% efficient detectors.* (It is a pity that we cannot know John Bell's reaction to this finding, because the paper with this model was still in press at the moment of his untimely death.) Consequently, not only are there loopholes in the Aspect experiments, but *these experiments cannot discriminate between QM and LHV theories*. They are therefore useless for the purpose for which they were designed (although they are quite interesting due to other implications, some of which will be discussed below). In view of this fact, the claim that LHV theories have been empirically refuted is wrong. In my opinion, the extension of this wrong belief is one of the greatest delusions in the history of twentieth-century physics.

Considering that non-ideal measuring devices are not the problem of the Aspect experiments, it is important to analyze how the model in [4] evades the argument, maintained by Bell (Ref. [5], see above) and many others that any LHV model for the Aspect experiment should disagree with QM for high efficiencies. The point where the argument fails is that the model does not allow defining the "subensemble of pairs such that both photons in the pair enter the apertures." The "passed subensemble" could certainly be defined in any LHV theory where the "photons" are indivisible entities, that is, particles (even if these particles are accompanied by guiding de Broglie waves). In sharp contrast, in a purely wave theory of light, where "photons" are just wavepackets, they may partially enter the apertures, and the "passed subensemble" cannot be defined. In conclusion, we might claim that *corpuscular LHV theories of light have been refuted by Aspect experiments*, suggesting a conspiratorial behaviour of nature, *but the claim is wrong for wave theories of light*. Today, 90 years after Einstein's historic paper on light quanta, it is widely believed that wave theories of light are untenable, but this opinion is not correct, as I will explain in the following.

The Hilbert space formulation of quantum optics suggests a corpuscular nature for photons. Photons are created and annihilated as space-time events; one photon never gives more than one detection event, *etc*. There are, however, other *fully equivalent* formulations of quantum optics which suggest a wave nature of light, namely phase space representations, such as the Wigner representation, the P (Glauber-Sudarshan) representation, or the Q representation. In particular, the function Q is positive definite and therefore may allow interpreting every quantum state of the electromagnetic field as a probability distribution of amplitudes. (These amplitudes play the role of the hidden variables in a hypothetical LHV model.) In this representation there is no trace of "corpuscles of light," there are only waves. Every quantum state of light is just a probability distribution of realizations of the electromagnetic field in space-time. I do not claim that taking the Q function as a probability distribution is the correct interpretation of quantum optics, but I conjecture that a purely wave theory of light (maybe using another phase-space distribution) may provide a LHV theory of quantum optics.

Simplified LHV models (not yet fully self-consistent) have already been found, which are able to explain every "nonclassical" aspect of light. The name "stochastic optics" (SO) has been proposed for this family of LHV models [7]. In particular, SO provides a natural (qualitative or semiquantitative) interpretation of all photon interference experiments which have been claimed to refute LHV theories in recent times [8]. An essential point of SO is the assumption of a real random background radiation filling the whole space, a radiation which just corresponds to the zeropoint field of quantum electrodynamics, but here taken as real. I should stress that SO has an important shortcoming, namely that it does not provide any good model for the interaction of light with atoms or molecules. Consequently it is necessary to make some *ad hoc* assumptions, *e.g.*, that photon detectors have a threshold so that only light signals above the "sea" of zeropoint radiation may be detected [7].

A more ambitious program, aimed to study the behaviour of microscopic systems, has been explored during the last 40 years under the name of "stochastic electrodynamics" (SED, see [7] for references). The program has had good success for linear systems, but has failed for nonlinear systems like the hydrogen atom. In my opinion SED (or its restriction to light, SO) represents a first step on the way towards the correct understanding of quantum theory in terms of local hidden variables.

1b. Does quantum mechanics violate the Bell inequalities?

The other argument against the possibility of LHV theories is the existence of a contradiction between LHV theories and QM, shown by Bell's theorem. My conjecture is that *Bell's theorem is not true*. I shall explain. The question whether there is a contradiction between QM and LHV may be answered only after defining precisely both terms of the comparison. If QM is understood as the nonrelativistic theory of particles with a finite number of degrees of freedom, then Bell's theorem is certainly true. However, if QM means relativistic quantum field theory, no rigorous proof has been yet given.

In other words, the proof of the theorem consists of two parts: 1) deriving a Bell inequality, valid for any LHV theory, 2) exhibiting an (eventually feasible) experiment where the quantum predictions violate the inequality. I have no objection to the first part, but I claim that no *real* (*i.e.* which may be actually performed) experiment has been found for the second part of the proof. All examples considered in the literature are highly idealized *gedanken* experiments. In particular, in all of them noise is neglected, when it is the case that *noise is the essential ingredient of quantum theory*. Indeed, relativistic quantum field theory (QFT) contains a fundamental source of noise in the form of vacuum fluctuations. This noise can never be fully removed, but it happens that quite good approximations to QFT can be found involving only a few degrees of freedom and no apparent noise, *e.g.*, nonrelativistic quantum mechanics or quantum optics (when dissipation is not included). This is the reason why elementary quantum mechanics cannot be understood from a realist point of view: it appears as a stochastic theory without noise (*e.g.*, Schrödinger equation is fully reversible).

In order to explain stochastic behaviour without noise, people are forced to introduce bizarre concepts like "essential indeterminacy," "interference of possibilities," "lack of causality," *etc.* My conjecture is that quantum noise may prevent the violation of Bell's inequalities in real experiments. The proof of the conjecture is not easy, but the disproof is also difficult. Indeed, no feasible experiment has been found truly able to discriminate between QM and the Bell inequality (recent proposals of "loophole-free" Bell experiments [9,10] depend on highly efficient photon detectors not yet achievable; my conjecture is that increasing the efficiency of detectors will also increase the noise, *e.g.*, in the form of dark rate, so that a Bell inequality will never be violated).

2. Most important unresolved issue in quantum physics today

The purpose of physics is to understand the world, not just to be able to predict (calculate) the results of the experiments. For many people the ability to predict provides a sufficient understanding, but not for me. This is the reason why I cannot accept the purely pragmatic (Copenhagen) interpretation of quantum mechanics. In my view, understanding the world means to be able to know causal relations between events, with influences propagating within light cones in agreement with relativity theory. We do not yet have an interpretation of quantum mechanics that fulfills these requirements and, in my opinion, this is the most important unsolved problem of physics at the end of the century. When this problem is solved, a wide avenue will appear for the solution of many other current problems in different realms: the unification of quantum theory and general relativity, which will allow a better understanding of cosmology and astrophysics; an information theory at the quantum level, which may allow more powerful computers and a better understanding of the behaviour of the brain; refined details of the structure and reactivity of molecules, which may further the development of biochemistry and molecular biology, *etc.*

In any case, until a satisfactory interpretation of QM is found, I prefer the purely pragmatic (Copenhagen) interpretation to the fashionable (realist?) alternatives, like "many worlds," "consistent histories," "Bohmian mechanics," *etc.* In my opinion they do not solve the problem either and the purely pragmatic interpretation may, at least, be presented as a provisional one, to be disposed of when a fully satisfactory interpretation is found.

I am firmly convinced that a good interpretation of quantum mechanics, which will be found sooner or later, should involve local hidden variables. I might try to explain in more detail the reasons for this belief, but the job has been done for me by Einstein in his "Autobiographical Notes" and "Reply to Criticisms" [11]. I subscribe to every word about the interpretation of quantum mechanics of these writings, but I shall quote just two sentences.

> *"The statistical quantum theory would, within the framework of future physics, take an approximately analogous position to the statistical mechanics within the framework of classical mechanics. I am rather firmly convinced that the development of theoretical physics will be of this type; but the path will be lengthy and difficult" (page 672). "On one supposition we should absolutely hold fast: The real factual situation of system S_2 is independent of what is done with the system S_1, which is spatially separated from the former" (page 85).*

It is true that Einstein never wrote the words "hidden variables," probably because he did not like the name (I also dislike it), but it is obvious to me that what he had in mind was precisely what today is known as a LHV (or local realistic) theory (see, *e.g.* Ref. [12], where this same opinion is defended).

3. The earlier debate (Solvay 1927)

It is well known that quantum mechanics appeared in 1925-26 in two quite different forms: wave mechanics (WM) and matrix mechanics (MM). WM originated from a combination of the ideas of wave-particle duality and relativity theory, both introduced by Einstein in 1905. MM was, at the beginning, a refinement of Bohr's quantization rules. WM attempted to give a picture of the world. MM began as a purely formal tool for making calculations. In this way, two schools emerged with a quite different opinion about the aim of quantum theory or, more generally, the aim of scientific theories. The founding fathers of WM (Einstein, de Broglie, Schrödinger) supported the realist view that science should give a causal, space-time, representation of the external world. In contrast, the creators of MM (Bohr, Heisenberg, Born, Dirac) thought that the only essential aim of science is to predict the results of experiments (although for many scientists the theory may also provide some picture of the world, this being a rather subjective matter). However, it is a fact that no objective world view free from contradictions emerged from WM in spite of great effort by many authors (although the valuable calculational methods of WM were incorporated into MM, giving rise to modern QM). This led to a sociological victory of the second school which was supported, and is still supported, by the mainstream of the physics community. However the representatives of the first school (specially Einstein) never renounced the search for an objective (realistic) world picture. They were supported by some of the most conspicuous philosophers of science, such as Popper and Bunge, who rejected the positivistic philosophy underlying the second school.

In some sense the situation is still the same. The views of the inheritors of Bohr still dominate the epistemology of modern physics. But the followers of Einstein still believe in the possibility of a deeper understanding of QM. It is paradoxical that one of the best representatives of the Einstein school in recent years, John Bell, was responsible for creating more trouble for progress along this line with his celebrated theorem.

There are, however, several important differences between the situation during the early days and recent times, which I summarize as follows: 1) Relativistic quantum field theory, found in the late forties opened the door for a better understanding of quantum theory, which is not possible for nonrelativistic quantum mechanics as explained above. 2) The stupendous experimental progress in dealing with microsystems (single atoms, single electrons, *etc.*), unbelievable a few decades ago, provides very useful information about quantum behaviour. 3) Bell's theorem has stimulated work on foundations and helped to clarify what is the true difference between classical and specifically quantum behaviour. 4) An increasing awareness has emerged that a purely pragmatic interpretation of quantum mechanics is unsatisfactory, and this has led to many recent (more or less "realist") interpretations, as noted above. 5) In particular, it is increasingly accepted that the quantum theory of measurement is in need of explanation. For instance, wavefunction collapse, which was just postulated in the early (Copenhagen) interpretations, is now under active scrutiny.

4. Future developments of foundations

I have already explained what I expect in the far future (a LHV interpretation of QM), and what I do not expect in the near future (a true violation of a Bell inequality). It is more difficult for me to predict progress in the near future, but I shall guess a few possibilities.

1. I am sure that the experimental progress in dealing with microsystems will not stop, but rather accelerate.
2. An increasing realization of the importance of the electromagnetic zeropoint radiation in atomic, molecular and solid state physics. It is known from the late forties that "photon dressing" was the main cause of the Lamb shift or, more generally, radiative corrections in QED. Also, its relevance has been shown in the last two decades by cavity QED experiments, vacuum squeezing, noise in measurements, *etc.* In my opinion, all these fields will greatly expand, but also new effects in molecules or solids will be discovered.
3. In close connection with the previous point, I predict an improvement of our understanding of the relation between stochastic electrodynamics and QED, which will take us closer to the final aim of a LHV interpretation of quantum theory.
4. Even if the problem of unifying quantum theory and general relativity is not solved (my conjecture is that it will not be solved before a satisfactory interpretation of quantum theory is available) I predict that new connections between quantum mechanics and gravity will be found.
5. The subject of the transmission of information at the quantum level will surely be clarified. This matter has not only fundamental, but also a considerable practical interest.

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Fundamental Problems of Quantum Physics

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1. Quantum theory vs. hidden variables

The experiments performed on Bell's theorem up to the present time are totally inconclusive concerning the possibility/impossibility of a causal and local description of physical reality, because of the essential role of some additional assumptions used for deducing the particular form of Bell's theorem with which the experimental data were confronted. It is for this reason that I have proposed to divide Bell-type inequalities into two groups: *weak inequalities* deduced exclusively from the assumption of local realism, and *strong inequalities* deduced also with the (essential) help of additional assumptions [1]. Weak and strong inequalities are not only conceptually, but also numerically very different: in the case of the 1981 Orsay experiments the measured physical quantify G had to satisfy $-0.850 \leq G \leq 0.150$ according to the weak inequality, while it was required to satisfy $0.000 \leq G \leq 0.014$ according to the strong one. The empirical result was $G = 0.015$ with a very small error, meaning that the strong inequality was violated while the weak one was fully compatible with the value found for G. A similar situation is met in the case of recent experiments on two-photon interference. In all cases the additional assumptions compare two or more incompatible behaviours of a single atomic system. Since any given system can only be detected once, the additional assumptions are not only arbitrary, but also metaphysical.

It should be stressed that Bell's inequality (the weak one) is a consequence not of any particular model of local reality, but of the most general definition of local realism that one can conceive. On this point, all the physicists who have worked on Bell's theorem more than occasionally are in agreement. It is, in particular, independent of the picture of the e.m. field that one may choose to adopt. Therefore, if in future experiments Bell's inequality is found to be really violated, then local realism will be dead forever. That would mean either that no objective reality exists at the atomic level, or that instantaneous superluminal information can be exchanged between objects separated by very large space intervals. In both cases one would obtain a very strange description of the atomic world, and this leads me to believe that Bell's (weak) inequality will not be found to be violated, after all, when experiments using high efficiency detectors are performed.

2. Most important unresolved issue in quantum physics today

The most fundamental question of modern physics in my opinion concerns the possibility of giving a rational description of physical reality, where rational means: developed also according to the ideas of causality, of three dimensional space, and of time. All the great men of classical physics sought such a description: Galilei, Newton, Maxwell, Boltzmann are some examples. In the 20th century, it has become fashionable to adopt a negative attitude about the comprehensibility of physical reality, following the opinions expressed in the late 20's by Bohr, Heisenberg and others. Formidable obstacles (the so-called "impossibility proofs") had been erected against the desire of many to bring physics back to causality in space and time: *von Neumann's theorem, Bohr's complementarity principle* and *Heisenberg's interpretation of his inequality as "uncertainty relations."* The new situation that has emerged just recently is that all such obstacles have been overcome. (See references [2], [3], [4].) Hidden variables are conjectured as new physical properties of atomic objects which would modify the quantum mechanical description, making it more accurate and in agreement with causality in space and time. There is, of course, nothing really "hidden" about these variables, the term having been introduced by physicists opposed to the causal description. Actually they are hidden only in the sense that quasars were hidden to astronomers before they were discovered. The assumption that hidden variables do not exist and therefore that quantum theory is complete has been called ridiculous by Karl Popper [5], and is known to lead to an incredible set of fantastic paradoxes, such as Schrödinger's cat, de Broglie's box, Wigner's friend, Wheeler's delayed choice. These paradoxes melt away immediately as soon as one takes the reasonable point of view that the present theory is incomplete. Their existence is therefore a sort of logical punishment for the arrogant assumption that a human theory should be perfect. Today people having a realistic attitude can freely try to enrich the existing theory, since the impossibility proofs have all been overcome, and in fact several physicists are active at this type of research. Given that "local realism" is practically the same as "causal description in space and time," Bell's theorem has itself become a sort of "impossibility theorem": any local description of reality must satisfy Bell's inequality and, consequently, disagree with quantum mechanics. Therefore, a rational description of physical reality will become fully possible only once the existing quantum theory is shown to be incorrect in some of its empirical predictions. The other possibility is to assume that what was considered rational in classical physics (a causal description in space and time) cannot be so at the atomic level. This is the solution favoured by the fans of the Copenhagen interpretation, but in recent times its complete arbitrariness has become evident. It should also be added that a fully rational description of atomic reality must (especially) provide a solution to the long-standing problem of wave/particle duality. It is very remarkable that of the many models proposed for describing the very rich empirical evidence only one survives today—the wave *and* particle model of Einstein and de Broglie. In my opinion its survival, after almost 70 years of quantum theory, is a very strong indication in favour of its validity in nature. Several experiments have been proposed that could lead to the direct detection of the propagation of quantum waves in space and time, and have been reviewed in a book [6].

3. The earlier debate (Solvay 1927)

The points in common with the debates that went on in 1927-1939 are very important. The "strangely turbulent developments"—as Einstein called them—that led to the formulation of the Copenhagen quantum theory also incurred the lasting opposition of Planck, Ehrenfest, Schrödinger and de Broglie. There is an iron connection between the opposition of those great men and the ideas put forward by contemporary opponents of the ruling paradigm. The disagreement is not centered on technicalities, but on the very reasons that lead mankind to the development of scientific theories. According to the opponents an acceptable theory could only be an attempt to obtain a better understanding of the true workings of nature. A simple mathematical description without a full physical understanding of the symbols used would not be enough. According to the Copenhagen and Göttingen schools, on the other hand, knowledge of the true workings of nature is impossible for men. Bohr expressed this key idea by stressing many times that he "advocated the application of the word phenomenon exclusively to refer to the observations." It is now clearer than ever that the pessimistic attitude of the founders of the quantum paradigm was due only to ideological choices, and in no way dictated by properties of nature. Its general acceptance was of course due to the subsequent building of a successful theory. From a pragmatic point of view, success is considered a decisive criterion, but modern epistemologists (Popper, Lakatos, Kuhn, *etc.*) have come to the rather obvious conclusion that several different theories can simultaneously explain any given finite set of experimental data. Therefore an equally successful but conceptually more acceptable quantum theory should be possible.

4. Future developments of foundations

It is difficult to be globally optimistic about the near future, because the scientific community has become very conservative as far as the foundations of modern physics are concerned. Physicists in an experimental group will normally find it very difficult to start a really fundamental research. Suppose they try to check experimentally the validity of some basic pillar of our science. There are two possible outcomes: If they found that the existing theory is correct, a lot of people would immediately say that this result was obvious and that it was a waste of money and of time to do the experiment. If they found instead that the existing theory is incorrect, the same people would say that their experiment is very probably wrong, and it thus becomes not even obvious that the experiment will soon be repeated by somebody else, leaving those physicists (possibly for a long time) open to the suspicion of having done a bad research. This kind of situation makes fundamental physics a very risky game, and there is an almost complete lack of heroes around. These are the consequences of the spreading of dogmatism within the scientific milieu. In the long run, in my opinion, the basic ideas of 20th century physics will very probably be radically modified. This was also Dirac's opinion. After a lifetime spent developing the Copenhagen approach, Dirac came to the conclusion [7] that: "There are great difficulties ... in connection with the present quantum mechanics. It is the best that one can do up till now. But, one should not suppose that it will survive indefinitely into the future. And I think that it is quite likely that at some future time we may get an improved quantum mechanics in which there will be a return to determinism and which will, therefore, justify the Einstein point of view."

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Fundamental Problems of Quantum Physics

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1. Quantum theory vs. hidden variables

It must be realized that quantum mechanics in its present state, as it is taught in universities and utilized in laboratories, is essentially a mathematical formalism which makes statistical predictions. In all known experiments, those statistical properties have been confirmed. The interpretation of such a statistical formalism is a different matter. The dominant, so-called Copenhagen interpretation of quantum mechanics states that there are no hidden variables behind these statistical predictions. In other words, the particle aspect of matter that appears in all experiments does not correspond to motions in space and time. There is nothing behind quantum mechanics and the statistical information provided by quantum mechanics represents an ultimate limit of all scientific knowledge in the microworld.

Since 1927, with ups and downs, alternative interpretations of the formalism have been developed in terms of real physical hidden parameters. It must be realized that these alternative hidden variable models are of two different, conflicting natures. In one version, the initial de Broglie-Bohm model, individual micro-objects are waves and particles simultaneously, the individual particles being piloted by the waves. This realistic model must of course be extended to many-body entangled particle systems. In this situation, the so-called hidden variable models split into two. In the first, local model, there is no such thing as superluminal correlations between the particles. This has led to Bell's research and the discovery of the so-called Bell inequality, which should be violated by non-local hidden variable models. This position has been defended to his last days by de Broglie himself, and some of his followers (Lochak, Selleri, Andrade da Silva, *etc.*).

In the second version the hidden variables engender non-local interactions between entangled particle states. This is the view defended by Bohm, myself, *etc.* These non-local correlations (which, by the way also appear in the quantum mechanical formalism) correspond to the superluminal propagation of the real phase wave packets which were introduced by de Broglie as the basis of his discovery of wave mechanics.

The present situation is very exciting because for the first time one can make experiments that detect photons and other particles one by one, and therefore, we are going to be able to test in an unambiguous way, the existence or not of superluminal correlations. In my opinion, the existence of these correlations has already been established not only by Aspect's experiments (I believe the improved version now underway will confirm his initial results), but they have also been established by down-converted photon pair experiments (Maryland experiments).

2. Most important unresolved issue in quantum physics today

There are two crucial questions in quantum physics today:

1. Do particles always travel in space and time along timelike trajectories? This of course implies the existence of quantum potentials and variation of particle energy along the path which results from the particle-wave gearing.
2. Do superluminal interactions conflict or not with relativity theory, in other words, are the observed non-local correlations compatible with Einstein's conception of causality?

Both points can now be answered by experiment. On the first point, experiments can now be made with neutrons, one by one, to test Einstein's *einweg* assumption in the double-slit experiment. It is also now possible to perform photo-electric experiments to show the existence of the quantum potential. On the second point, calculations started by Sudarshan and other people have shown that non-local correlations preserve Einstein causality provided the Hamiltonians of entangled particles commute, and it has been shown that the quantum potential in the many-body system built by Bohm, myself, *etc.*, satisfies this causality condition. In other words, quantum non-locality can now be considered as an experimental fact which satisfies Einstein's causality in the non-local realistic interpretation of hidden variables.*

* This non-locality rests on the idea that the particles and the wave constitutive elements are not delta functions, but correspond to extended hypertubes (which contain real clock-like motions) which can thus carry superluminal phase waves.
If the existence of a gravitational field which determines the metric is confirmed, gravitational interactions could also correspond to spin-two phase waves moving faster than light.

3. The earlier debate (Solvay 1927)

On the third question, the present debate is an extension of the Solvay controversy. At that time, there was no possibility to realize in the laboratory, Einstein's or Bohr's gedanken experiments. The situation is now different, so that the Bohr-Einstein controversy and the discussion between proponents of local or non-local realistic quantum mechanical models are going to be settled by experiments.

4. Future developments of foundations

In my opinion the most important development to be expected in the near future concerning the foundations of quantum physics is a revival, in modern covariant form, of the ether concept of the founding fathers of the theory of light (Maxwell, Lorentz, Einstein, *etc.*). This is a crucial question, and it now appears that the vacuum is a real physical medium which presents surprising properties (superfluid, *i.e.* negligible resistance to inertial motions) so that the observed material manifestations correspond to the propagation of different types of phase waves and different types of internal motions within the extended particles themselves. The transformation of particles into each other would correspond to reciprocal transformations of such motions. The propagation of phase waves on the top of such a complex medium first suggested by Dirac in his famous 1951 paper in *Nature* yields the possibility to bring together relativity theory and quantum mechanics as different aspects of motions at different scales. This ether, itself being built from spin one-half ground-state extended elements undergoing covariant stochastic motions, is reminiscent of old ideas at the origin of classical physics proposed by Descartes and in ancient times by Heraclitus himself. The statistics of quantum mechanics thus reflects the basic chaotic nature of ground state motions in the Universe.

Of course, such a model also implies the existence of non-zero mass photons as proposed by Einstein, Schrödinger, and de Broglie. If confirmed by experiment, it would necessitate a complete revision of present cosmological views. The associated tired-light models could possibly replace the so-called expanding Universe models. Non-velocity redshifts could explain anomalous quasar-galaxy associations, *etc.*, and the Universe would possibly be infinite in time. It could be described in an absolute spacetime frame corresponding to the observed 2.7 K microwave background Planck distribution. Absolute 4-momentum and angular momentum conservation would be valid at all times and at every point in the Universe.