1984-4

O. COSTA DE BEAUREGARD

TIME SYMMETRY AND INTERPRETATION OF QUANTUM MECHANICS

1. INTRODUCTION: PARADIGM AND PARADOX

There is something truly paradoxical in quantum mechanics. Physicists know well how to use it for explaining or predicting an ever-increasing harvest of phenomena, some of which are striking, even to the expert. Nevertheless, and notwithstanding the appearance, even recently, of some sedative writings by both physicists ([1]–[6]) and philosophers of science, it is clear that many among the leading theorists ([7]–[9]) and the fervent epistemologists ([10]–[13]) remain unsedated by the tranquilizing sort of remedies and keep suspecting that the problem of properly interpreting quantum mechanics may well conceal a major enigma.

In other words, the solution of the various well-known paradoxes by Einstein, Schrödinger, Wigner, and others may well imply the recognition and the understanding of one central, major paradox, out of which all the others are generated.

It seems to me that this problem – *understanding* quantum mechanics, and not merely *knowing how* to use it – has implications somewhat similar to those of the relativity problem confronting Einstein in 1905. In 1905 the relativity problem was an old one, originating much further back than the 1887 second-order null effect of Michelson: from the 1818 first-order null effect of Arago by means of a group-theoretical argument, as emphasized by Hadamard[4] [1] or even, as Yilmaz [16] convincingly argues, from the 1728 Bradley effect and consistency of Fermat's principle.[2] Through the years it had been a problem ever more replete with paradoxes, which called forth an ever-increasing flow of thought, calculations, and experiments. It was a problem where one *knew how to use the right formulas* (once these were found: Fresnel's 'ether drag' formula and the Lorentz-Poincaré formulas, already known to Larmor in 1898 and – not quite exactly – to Voigt in 1887), *but one did not known how to read them*. What was missing was just the epistemology and the discourse neatly fitting these 'good' formulas and faithfully rendering, in the world of concepts, their group property. The problem was thus not one of more sophistication in the mathematics, nor in the axiomatics. As they stood, in their elegant simplicity, as unveiled by Poincaré[17] and

R. S. Cohen and M. W. Wartofsky (eds.), Physical Sciences and History of Physics, 35–56.

later by Minkowski,[3] the mathematics was all right. Playing with the axiomatics, as has been long fashionable after Einstein's discovery, was not the answer either. No, the problem was just plain reading of the Lorentz-Poincaré formulas or of the Fresnel ether drag formula([14], [15]), *faithfully rendering their group property*. This would bring in quite smoothly the relativity of time and space, however paradoxical this epistemology has seemed to be and this discourse has sounded. The prophet, of course, who unveiled the sense of the scriptures was Einstein, in his 1905 paper, where none of the mathematics is new. The breakthrough lay entirely in the interpretation, thus bringing all the old paradoxes to the point of radiance as one dazzling, but illuminating, new paradox – very much as Copernicus had done in older days and under other circumstances.

This brings me naturally to the crucial role of paradoxes and their akinness to paradigms [18]. One reads in Funk and Wagnall's *Standard Dictionary of the English Language* the following definition: "Paradox: 1. *A statement, doctrine or expression seemingly absurd or contradictory to common notions or to what would naturally be believed, but in fact really true.*" There is no doubt that Copernicus and Einstein's statements and doctrines have been paradoxical in this primary sense, and that they exemplify a process that is quite common in the advancement of science. Science, in its acrobatic advance along the rope, always oscillates between modelism and formalism. Maxwell's and Boltzmann's statistical mechanics (but not Gibbs') can be taken as a victory of modelism, while Kepler's three laws, or Einstein's and Minkowski's relativity, are triumphs of formalism. Formalism, in its clever simplicity, dissolves the clumsy constructs of modelism – for instance, the mechanical theories of the ether – very much like that stone in the Book of Daniel (Ein Stein), which came full speed from elsewhere, and reduced the composite colossus to pieces.

It also happens that the new synthesizing paradox assumes and gives sense to a few small paradoxes (in Funk and Wagnall's fundamental sense) which have kept creeping in through the ages and were taken as superstitions. For example, falling meteorites, an obvious fact to farmers or hunters, were still a superstition to Laplace in the eighteenth century, while in the early seventeenth century a scholar wrote that "Briton sailors are so superstitious that they believe the Moon has an influence upon the tides." One need not say that these two superstitions have become part of the religion in Newton's gravitation theory. The paradox of action at a distance has assumed both of them.

Finally, the position I am taking is that the problem of interpreting or understanding quantum mechanics is essentially one of plain unbiased reading of the 'good' (that is, the very operation and elegant) formalism we already have, thanks to Heisenberg, Schrödinger, Dirac, and others. This I believe – and intend to show – will uncover a very new but also illuminating central paradox, one that will incidentally assume and perhaps render more respectable one or two superstitions.

2. COLLAPSE OF THE WAVE PACKET: AN ACTIVE INTERVENTION OF THE PSYCHE

Among the ever-flowing deluge of papers devoted to the interpretation of quantum mechanics, I select Moldauer's ([3], [4]) very valuable work, not only because it aptly clarifies some important technical points, and it is representative of those ([1]–[5]) who, by asking, "Is there a quantum measurement problem?" imply that there is none, but mainly because it shows quite clearly at which point the central issue is sidestepped. Moldauer writes [3]: "This paper does *not* deal with... the following questions: Is a probabilistic theory a sufficient description of phenomena that have only statistically reproducible properties? What is the precise meaning of probability?" *These* are the embarrassing issues I am aiming at. As long as they are swept under the rug, the dust will keep trickling out, and then the most clever axiomatics or competent mathematics will not prevent the audience from coughing from time to time. This I do, when Moldauer writes elsewhere [3], "The consequent reduction of the state vector . . . is completely described by the combined tools of the Schrödinger equation and the statistical interpretation. . . ."

The critical point is the interpretation of the *stochastic event* that *occurs* when a *transition* takes place, and when *one* among the various *a priori* possibilities (each endowed with a suitable probability) is actualized. In classical statistical mechanics it was *assumed* that stochastic events do occur, the frequencies of which reproduce (in repetitive tests) the calculated probabilities. *Mutatis mutandis* (and, of course, some of the *mutata* are highly specific), this classical trait reappears in von Neumann's quantal ensembles. But *this* is definitely *not* the point, and various axiomatic approaches expertly playing with the density matrix sidestep it.

The central problem is *what occurs* in the *individual* quantal transition – the preliminary answer being that nothing in the quantal formalism tells us *what*. I believe I have read in an article (but know not where, so perhaps I have dreamt it), that there is *nothing* in the quantal formalism speaking by itself of an event.[4] This is the point, and it is very clearly stated in two early works: von Neumann's [19], where it is implicit everywhere, and London and Bauer's [20], where it is quite explicit. And the very same answer to the problem was put forward in these works: The *event* or *transition* that is expressed formally as *collapse of the state vector* (into one of its orthogonal components) occurs when, and only when, the observer takes cognizance of the experimental result. Thus, the quantal stochastic event is neither purely objective, because it *would not* occur in the absence of some sort of consciousness registering it, nor purely subjective, because it truly occurs in the real world. In other words, the quantal stochastic event *must* be thought of as *indissolubly objective and subjective* – a trait which I have long believed [21]–[23]) to be intrinsic to *true* or *essential* probability – if only because the purely objective and the purely subjective schools both run into severe difficulties. Thus it may well be that the quantal stochastic formalism is much nearer than the classical one to an adequate expression of *essential* probability. In this respect Landé [24] has significant things to say, but I will not delve into them here.

Perhaps I should quote, as supporting what I am saying, a few sentences from a very searching article by Hooker [12]. Hooker argues against both Jauch's treatment of the Einstein-Podolsky-Rosen (EPR) paradox and Krips's treatment of the Schrödinger cat (SC) paradox. He writes, "One wants to know what precisely is *physically* going on in a single given instance of the measurement process when this transition is supposed to be occurring. No answer seems to be forthcoming from quantum theory." And a little later,

> Which one of the statistical possibilities is in fact realized when the measurement process is over is not represented in the theory until some human observer 'takes a look' and decides on the basis of that look to change the state representation from the statistical mixture to some particular pure state. This kind of change is commonplace, of course, in classical statistical theories, and it provokes no comment there precisely because we do not take them to be offering a complete description of physical reality. But only Einstein and the like-minded have continued to argue this status of quantum theory itself.

This being said, I certainly do not pretend that Prof. Hooker is ready to follow me in what I will be stating later.

Concluding this section, I cannot see any possible escape from the twin statements: (1) Quantal transitions, as a specific sort of stochastic event, do occur, and they imply a discontinuous jump, or collapse, of the state vector; and (2) as von Neumann, and London and Bauer, have stressed, the state vector collapse in an individual transition is due to an act of consciousness on the observer's part.

3. INTRINSIC STATISTICAL TIME SYMMETRY AND ARISTOTLE'S TWOFOLD INFORMATION CONCEPT

Let me recall that the problem of understanding physical irreversibility in terms of probability theory has turned out to be far more subtle than it had seemed at first. The appropriate answer to the well-known Loschmidt and Zermelo paradoxes has been clarified only recently by quite a few physicists and/or philosophers of science, who had started thinking independently and have come to an essential agreement, even if they stress different aspects of the question, or perhaps differ on some minor points.[5]

Essentially, the irreversibility paradox is inherent at the very start of probability theory, where it is given a technical answer by means of Bayes' conditional probability formula. The paradox is that, given some initial complexion of a stochastic system – say, a deck of cards – a 'blind statistical prediction' of the issue of a test, or transition – say, of shuffling the cards – will be operational, while a 'blind statistical retrodiction' will not.

Nobody will rely on shuffling to put the deck in order. At least this is the situation prevailing in physics, where of course it is very tightly connected with the second law of thermodynamics. A radioactive nucleus will decay spontaneously according to the laws of probability, but no physicist expects that stray electrons and neutrinos will converge toward a cell containing ^{11}B and fill it with ^{11}C. In other words, blind statistical prediction is physical while blind statistical retrodiction is not. And this *cannot* be accounted for by the intrinsic transition laws, which are, in most cases, taken to be time symmetric[6] – as, for instance, in card shuffling or in radioactivity.[7] For this reason, retrodictive physical problems are treated with the aid of Bayes's conditional probability formula, that is, by using not only the *intrinsic* transition probabilities, but also a set of *extrinsic* probabilities (Bayes' coefficients), which are estimated according to one's idea of the situation, and obviously represent at best the *initial interaction* out of which the stochastic system under consideration is born. This use of Bayes' formula is the technical trick expressing the fact that blind retrodicition is forbidden in physics. To my knowledge, van der Waals [25] was the first to point out that the statistical interpretation of Carnot's principle is a specification of Bayes's principle, while the same idea is implicit in an often-quoted sentence by Gibbs [26].

But *knowing how* to express the fact that blind statistical retrodiction is forbidden does not *explain why* physical interactions *macroscopically* produce after-effects rather than before-effects. If, between times t_1 and t_2, a physicist moves a piston along the wall of a vessel containing a gas in equilibrium, Maxwell's velocity law will be disturbed after time t_2, but not before time t_1. The perturbation will be emitted as a divergent, or retarded, pressure wave and not absorbed as a convergent, or advanced, wave. This example displays a one-to-one connection between the principle of increasing probability – the second law – and the principle of retarded waves – the principle of causality. This point has been fully clarified only recently,[8] but the classical physicists must have guessed it in some sense, since they termed their use of Bayes' principle in retrodictive problems *the principle of probability of causes*. Symmetrically, there is also a one-to-one association between the two (unphysical) principles of decreasing probabilities and of advanced actions; on this side, the connection with the philosophical concept of finality has always seemed obvious. Let me mention Bergson [27] as making a strong case of finality as an (at least seemingly) anti-Carnot process, and the Italian mathematician Fantappie [28] as conceiving finality as an advanced wave process.

So, the search for the root of physical irreversibility leads to the conclusion that it is not at all intrinsic in the elementary laws of evolution (see Note 8), but rather that it emerges macroscopically as a *boundary condition* imposed upon the integration of the Boltzmann or the 'master' equation. This is in striking analogy with the physics of waves, where irreversibility is similarly absent from the so-called wave equation, and appears only via the boundary condition chosen when the equation is integrated. This suggests the existence of a physical connection between the two statements, which can indeed be displayed in the realm of quantized waves, as I will discuss in the next section.

Now, as I have said, my philosophy in this paper is to rely *completely* on the formalism, so that interpreting the formalism builds an epistemology isomorphic to the intrinsic symmetries of the formalism, just as a well-cut dress is isomorphic to the body. This it seems to me was Einstein's work as founder of the relativity theory. Or, to take an example better suited to our symmetry problem, the 'hole' in Dirac's electron theory has been exactly filled by Anderson's positron – a quite unexpected and rather rare phenomenon. The *de facto* very large dissymmetry between the rare positron and the trivial electron does not preclude their *de jure* complete symmetry. *I thus feel logically justified in taking anti-Carnot processes, that is, advanced action* *processes, as macroscopic ones that are not strictly forbidden, but are usually rare, or at least do not occur in the typical physical context.* It then remains to be discussed whether perhaps they could not appear under appropriate conditions. If so, and if the twin (macroscopic) principles of increasing probability and of retarded actions are taken to be an essential part of *physics*, then the hypothetical context I am alluding to should be termed *antiphysical* – very much as the positron is termed an *antielectron*. I am well aware that this direction leads me straight toward paradoxes in the strongest sense. This I will accept boldly, remembering not only the dictionary's definition, but also that the 'strange' world of antiparticles has become a scientific El Dorado. Let us run the risk that perhaps the very strange world of antiphysics might also be a scientific El Dorado. . . .

The intrinsic time symmetry I am discussing has important consequences in the question of physical equivalence between negentropy and information. The discovery of this equivalence, which is the very heart of cybernetics, is another instance of multiple independent discovery by mathematicians, physicists, and engineers.[9] Let us equate the essence of this discovery with the two faces of a medal: heads and tails. Are we not speaking of games of chance?

The first major discovery of cybernetics, as Gabor put it, is that "one cannot get anything from nothing, not even an observation". One cannot obtain information by reading, listening, or sensing in any way, without the negentropy of the environment diminishing by an amount at least equal to the information that is gained. Both concepts, information and negentropy, are defined through the same mathematical formula: the logarithm of a probability. Thus cybernetics interprets the gain of knowledge – "getting information," in the words of the man in the street, when for instance he buys a newspaper – as a generalization of the passive Carnot process. Instead of letting the negentropy of a closed system become uselessly degraded, one can recapture part – or, ideally, the whole – of it, in the form of knowledge.

The other facet of the discovery is that existing information can be used to produce macroscopic order, the 'negentropy' thus generated being at most equal to the information that has been invested. A typical instance of this is the activity of Maxwell's demon, as intrepreted by Brillouin and other cyberneticists. In this respect *information* appears as an organizing power or, in other words, as power of action or of will.

What is truly astounding is that for Aristotle – the proponent of both the concept and the word – information was a towfold entity: *knowledge* one could acquire, and an *organizing power* one could use. Without having sought it, cybernetics has precisely hit upon the two facets of the Aristotelian concept.

Now, the *fact* (if not the *legal right*) is that the first Aristotelian meaning, gain of knowledge, is trivial to everybody, while the second one, organizing power, is somewhat esoteric and familiar only to those few philosophers interested in will and finality. I believe ([21]–[23]) this *fact* to be a mere corollary of the other *fact* noted above, the extreme preponderance of entropy- (or probability-) increasing processes[10] over decreasing ones, which is equivalent, as we have seen, to the preponderance of retarded (macroscopic) waves over advanced ones. This implies as a consequence an extreme preponderance of the passive, learning transition, over the active, willing ones. Very much like positrons among the crowd of electrons – needles in a haystack – so are advanced action phenomena scattered among the Niagara cascade of retarded action phenomena. That is, so are final processes as compared to causal ones. Or (in terms of the subjective side of the probability concept), conversely, so is willing awareness more strongly sensed than learning awareness.

It should be obvious that the very values of the universal constants of physics in terms of 'practical' units directly reflect man's existential situation. For instance, if Einstein's constant c, the speed of light, is very large when expressed in, say, meters and seconds, it is because man finds it convenient to view meters and seconds as associated standards of length and time. This may very well be because the velocity of our nerve impulses is of the order of meters per second. For this simple reason the relativistic phenomena lie far beyond the observation range of everyday experience. Things would be completely different if the velocity of our nerve impulses were some large fraction of c. *Mutatis mutandis*, I believe the situation to be very much the same with respect to negentropy and information. The conversion coefficient between a negentropy expressed in 'practical' thermodynamic units and an information item expressed in its natural binary unit is Boltzmann's constant k (more precisely, it is $k \ln 2$), and this is quite small. Thus, gaining knowledge is extremely cheap in negentropy terms, while producing negentropy costs a lot in information terms. This existential state of affairs directly reflects the *fact* that our world is a Carnot world, where retarded actions outweigh advanced actions.

Significantly, I believe, the universal constants of the major twentieth century theories are exceedingly small, or large, as expressed in 'practical' units. Besides Einstein's c and Boltzmann's k,[11] the other example is of course Planck's h. The implication is that all these important aspects of twentieth century physics lie far outside the domain of man's everyday experience.

Now, it is a familiar sort of exercise to see how, by taking an extremely small universal constant to be zero (or a very large one to be infinite), one falls back on the familiar state of affairs and loses the far-reaching, or 'paradoxical,' insight that comes with scientific novelty. Thus, by taking $1/c$ to be zero, one loses Einstein and recovers Newton, or, by taking Planck's h to be zero, one loses Einstein's photons in optics and de Broglie's matter waves in mechanics.

What are we losing if we take Boltzmann's k to be zero? We render learning more than cheap: gratuitous. And we render acting through will more than costly: impossible. This is a theory that was very fashionable in the nineteenth century under the name of *epiphenomenal consciousness.*

The cybernetic discovery is that consciousness, as a spectator, must buy its ticket for one dime or two. But this alone is sufficient for allowing it to become an actor also. Thus, our task is now to look beyond the *de facto* Carnot situation that hides the deeper questions by properly 'shuffling the cards'. We have to understand the *de jure* symmetry concealed behind the *de facto* asymmetry. And this might well expose novelties more paradoxical than the positron.

A quotation from Brillouin [30] may be in order at this point. He writes: "Relativity theory seemed, at the beginning, to yield only very small corrections to classical mechanics. New applications to nuclear energy now prove the fundamental importance of the mass-energy relation. We may also hope that the entropy–information connection will, sooner or later, come into the foreground, and that we will discover where to use it to its full value."

4. INTRINSIC QUANTAL TIME SYMMETRY AND COLLAPSE OF THE STATE FUNCTION

Although the specific rules of the original sort of probability calculus inherent in quantum mechanics are markedly different from the classical ones, all the essentials of the preceding analysis are retained in it. Discarding the rare case of some weak interactions that are T-violating, we can state that the intrinsic predictive probability that a quantum state A goes into a quantum state B is equal to the intrinsic retrodictive probability that state B has come from state A. This is the intrinsic stochastic time symmetry of quantum mechanics, which must be reconciled with the macroscopic time dissymmetry so evidently displayed, for example, in radioactive decays or electromagnetic radiation. The technical answer is the same as before: Whenever we are speaking not of one single quantal transition, but of a macroscopic ensemble of transitions, blind statistical prediction is physical while blind statistical retrodiction is not. And here, in quantum mechanics, the one-to-one association of increasing probability and retarded waves on the one hand, and of decreasing probability and advanced waves on the other hand, is very much tighter than in classical statistical mechanics. This is because the probability concept and the wave concept are both inherent in quantum mechanics – an association that might well be of very deep significance for natural philosophy. As Fock [31], it seems, was the first to state explicitly, retarded waves are used in quantum mechanics for statistical prediction, while advanced waves should be used for statistical retrodiction. Thus, 'prohibition of blind statistical retrodiction' and 'macroscopic nonexistence of advanced waves' are merely different wordings of the same statement. Incidentally, this reconciles the apparently contradictory opinions of Einstein and Ritz in their famous controversy [32]. For Ritz, probability increase implied a postulate of wave retardation, while for Einstein wave retardation should be understood as a consequence of probability increase. It is clear today that these two statements are *reciprocal*. Moreover, both express a *de facto* situation expressible as an initial (not final) boundary condition. If this was not clear in the days of Einstein and Ritz, it is because while Einstein's light quanta were then known, de Broglie's waves were not. It was thus not obvious that wave scattering and particle scattering go physically hand in hand.

A very neat way of displaying ([21]–[23]) the reciprocity of the two laws of probability increase and of wave retardation uses the formalism of von Neumann's [19] quantal ensembles. It is, in fact, a mere rewording of his irreversibility proof. The quantal entropy is found to increase at each transition *if* retarded waves are used between two interactions. Otherwise, the entropy would decrease.

The interpretation of quantal entropy as information is quite transparent in von Neumann's well-known book. The explicit demonstration has been given by Jaynes [33] in the second of his two pioneering articles on statistical mechanics. It had been partially expressed earlier by Elsasser [34]. In fact, the quantal version of Jaynes' reasoning is a truly natural sequel to von Neumann's quantal ensemble theory.

With Jaynes' formalism at hand, it is merely routine to extend, in quantum mechanics, all that has been previously said of Aristotle's twofold information concept, and of the *intrinsic* symmetry between *gain in know-*

ledge and *organizing power*. So, here again, we face the problem of giving an operational meaning to that semipopulation of entities that seem to exist only as abstract concepts: *macroscopic advanced waves* and *information as organizing power*. However, we have in our hands a magic wand for conferring life to these ghosts, a magic wand that was missing in classical statistical mechanics. As stated by von Neumann [19], London and Bauer [20], Wigner [9], and others, *the quantum event occurs if, and only if, there is an active intervention of the psyche*. So now we *really* have to understand what sort of being is the (still evanescent) ghost appearing in our formalism. *We have to track our positron.*

One last remark is in order, however, and it pertains to relativistic covariance. Relativistic covariance and waves naturally belong together, as explained by Einstein in 1905 and by de Broglie in 1925. The basic wave equations of quantum mechanics are all relativistically covariant, and Tomonaga, Schwinger, and Feynman have endowed the quantum field theory with complete relativistic covariance. What is perhaps less well known, and is at present important, is that the basic, so-called 'first quantized' formalism lends itself very well to full relativistic covariance.

Following a hint by Riesz [35], I have developed this formalism in articles, and finally in a book [36], while Wightman and Schweber [37] were producing similar formulas. Thus there will be no problem with relativistic covariance when we later tackle the EPR paradox (among others).

But relativistic covariance entails a more fundamental lesson. It has been said that relativity theory had lost the subject of the verb *to undulate*. If so, wave mechanics or quantum mechanics has hit upon the unforeseen subject of the verb – and one very different indeed from the lost *ether*. What is undulating through the vacuum, as explained by Dirac [38] and by Landé [24], is *the amplitude of the probability*. Dropping technical precision, we can speak of quantal waves as probability waves, or information waves. That is, when we speak of von Neumann's ensembles, *retarded, predictive waves are waves of cognizance, and advanced, retrodictive waves are waves of will.*[12]

5. BRINGING A GHOST TO LIFE AND SCHRÖDINGER'S CAT PARADOX

The ghost present in the formalism, thought to be absent from reality, is advanced waves in some macroscopic sense, displaying an existence of finality, or, in other words, an operational character of willing awareness.

Where are we to look for this anti-Carnot, anti-causal, anti-learning forlorn twin? The symmetry principle guiding us is not the same one as that behind the search for antiparticles, but our hope rests on a similar faith – that symmetry in the formalism is not misleading.

First we must discuss the stochastic event expressed as *collapse of the state vector*; it is also termed *quantal transition*. If this collapse needs the active intervention of some psyche, even in the cognitive or 'passive' case of impartial observation', *it precludes independence of two observations of the same event. They must cooperate (or perhaps compete) in producing the result.* And if they occur in succession, it seems that usually (but not necessarily always) the first one has far more weight, and that any following one is then bound to confirm its finding. One need not say that *these statements imply a very drastic reinterpretation of von Neumann's arbitrary severance between the observer and the observed system.*

For instance, in the Schrödinger cat problem there is by hypothesis a first informed observer – the cat.[13] The psyche (if any) that produces the wave collapse is the cat's – and usually not that of any of the psychobiologists versed in quantum mechanics who theorize before opening the box.

But if we believe in symmetry between cognizance and will, we are logically led to the working hypothesis that *collapse of the state vector can be caused not only by knowing awareness, but also by willing awareness.* If so, the cat should be able to influence the yes-or-no outcome to which he is subjected. And if so, one guesses that a normal cat will be in favor of the *yes*. At this very point we are hitting upon a 'superstition', upon a paradox from below, like that of meteorites, or of the Moon causing tides. For what we are speaking of has a name in the realm of parapsychology, and that name is *psychokinesis.*

Since a paradox, even one of the *below* kind, can certainly not be refuted by simply stating that it is contrary to common sense, we are led to inquire if perhaps parapsychologists have not already performed the Schrödinger cat experiment as we have just defined it. Well, they have; and if not with cats, at least with rats or with cockroaches. And if not as a 'death or life' dilemma, at least in a 'reward or punishment' fashion. And, as I have been told, they have done it with consistent success. They have found that the statistics of a random-outcome generator, tested before and after the psychokinetic experiment (and found to be perfectly normal in both tests), are systematically deranged when the animal is in the box, and this, of course, in the way favoring the animal – that is, more rewards, or less punishments. This kind of experiment has been done not only with classical, but also with quantal random outcome generators. The latter case is of course by far the most directly significant. The experimentalist is the physicist, Schmidt ([39], [40]).

Perhaps I should also quote a letter to the Editor of *Science* [41]. It reads: "During the past year I have had some correspondence with J. B. Rhine which has convinced me that I was highly unfair to him in what I said in an article published in *Science* in 1955 (26 Aug., p. 359). The article discussed possible fraud in extrasensory perception experiments. I suspect that I was similarly unfair in what I said about S. G. Soal in this paper. Signed: George R. Price".

So let us proceed. It is trivial to everybody that a single statistical quantal outcome, say, that an electron from a decaying radionuclide goes or does not go through a Geiger counter, with respective probabilities $\Omega/4\pi$ or $1 - \Omega/4\pi$, is recorded via an amplifying procedure using macroscopic retarded waves (perhaps in the form of the ultimate feelings of a cat). But, symmetrically, it sounds fantastic that an animal inside a box, where he is the innocent toy of a reward-or-punishment stochastic gadget (working through quantum statistics), can learn enough about what is going on that, by looking backward in time through the amplifying mechanism (whatever it is) by means of advanced waves, he should be able to act upon the elementary state vector collapse so that this transition, instead of being the source of a retarded wave, as usual, is the sink of an advanced wave. This is 'paradoxical'. But it is logical, as soon as we believe that matter waves are information waves, and that all their stochastic formalism is *intrinsically* time-symmetric. If we then call *reading* the (causal) use of retarded waves, we should term *antireading* the (final) use of advanced waves.

One need not emphasize that the taboo we here trespass against was labeled 'no reaction to the observer's glance by the measured system'. This taboo should be taken as *de facto* rather than *de jure* – and we are here deliberately taking liberties with good manners. Also, it has often been written that it is the finiteness of Planck's constant which obliges one to consider the reaction of the measuring device upon the measured system. Things are not exactly so. What the finiteness of Planck's h makes real is the one-to-one binding between increasing entropy and retarded waves. The reaction of the observer's glance upon the measured system is brought in by the finiteness of Boltzmann's k, and was already inherent in the very concept of Aristotle's twofold *information. In other words, it is inherent in the very idea that the probability concept is both objective and subjective, being the hinge around which matter and psyche are interacting.*

6. EINSTEIN-PODOLSKY-ROSEN PARADOX

The Einstein–Podolsky–Rosen paradox [42] is perhaps the most famous of the quantum paradoxes. It is a variant of other paradoxes due to Einstein [43], Schrödinger [44], and Renninger [45]. I have more than once thought (or dreamed) about the vicious sting intrinsic in the EPR paradox, and it is this meditation which, more than anything else, has convinced me[14] that *the essential nonlocality displayed in it* (and analyzed by Bohm [49], Bell [50], Shimony [51], and others) *cannot be understood otherwise than through the intrinsic past-future and cognizance-will symmetries.*

The first thing that should be made clear is that the distant correlation in the EPR paradox is definitely not of the trivial sort existing in classical statistical mechanics. If, say, a positronium atom rotating at point $\mathbf{r} = 0$ is made to explode at time $t = 0$ by an energy (and momentum-less) excitation, a measurement showing that the decay electron passes through point $\mathbf{r}_A$ at time $t_A = r_A v$ makes sure that the decay positron passes at time $t_B = t_A$ through the distant point $\mathbf{r}_B = -\mathbf{r}_A$. This is because of the law of conservation of momentum and has nothing paradoxical if one believes in hidden determinism. The quantal sort of correlation is of a more subtle character, as emphasized by d'Espagnat ([7], pp. 99–139) and, of course, by the calculations of Bell and Shimony. There is, nevertheless, a lesson to be gained ([46]–[48]) from the classical case. It is that the logical inference that deduces what is happening around the spatially distant point-instant $(\mathbf{r}_B, t_B)$ from the measurement made around the point-instant $(\mathbf{r}_A, t_A)$ is not telegraphed along the spacelike vector $(\mathbf{r}_B - \mathbf{r}_A, t_B - t_A = 0)$, but rather along the two timelike vectors $(-\mathbf{r}, -t_A)$ and then $(\mathbf{r}_B, t_b)$. Of course the symmetric statement would hold if an inference were drawn as to what happens in $(\mathbf{r}_A, t_A)$ from a measurement in $(\mathbf{r}_B, t_B)$. Also, nothing, of course, prevents two observers α and β from operating one on the electron A and the other on the positron B. That sort of space–time telegraph works both ways.

Why then does the quantal statistical correlation have very surprising characteristics that are absent in the classical one? Because, of course, the mathematics is different. More specifically, Bell and Shimony have shown that the form of the mathematics of the quantal correlation in the EPR situation is incompatible with the idea that the two diverging subsystems are governed by some hidden parameters belonging separately to each of them.[15] Therefore we have what d'Espagnat calls the *nonseparability* of these two subsystems (which, by hypothesis, have interacted in the past or, in the

Minkowski space–time scheme, are indeed coupled *sub specie aeternitatis*). Also, in an analysis by d'Espagnat, it is emphasized that if the two subsystems were thought to have each their own attributes, their union would be represented as a (particular) mixture. What are, then, the quantal facts?

At any time the total evolving system can be represented as being potentially a mixture with respect to the orthogonal states corresponding to a pair of associated possible measurements, but *then not* as a mixture with respect to the states of a pair of associated magnitudes that are not simultaneously measurable with the preceding ones. We are speaking, for instance, of the pair of x spin components and of the pair of y spin components of the electron and positron issuing from a spin-zero positronium atom. Until the very last moment, observer α, say, may hesitate as to which Cartesian component of the spin of particle A he will measure. However, as soon as he makes up his mind and performs the measurement, he is sure that if observer β measures the corresponding spin component of B, he *does* find the value that is strictly correlated to the one he has found himself. In this case we have not only telediction, as in the classical situation, but also teleaction, in the sense that, when α performs his measurement on A, a transition truly occurs there, and that the *same* transition certainly occurs in B if β performs the measurement corresponding to that of α.

Now, *the formalism clearly shows that this telediction-and-teleaction is telegraphed not directly along the spacelike AB vector but (like the telediction in the classical case) along the two timelike vectors AO and OB* (*O* being inside the space-time domain where the two subsystems are generated). The *AOB* or *BOA* zigzag is similar in many respects to a Feynman zigzag.

In my philosophy, where advanced actions are postulated to exist, and to be operational in some specific cases designed *ad hoc*, the EPR situation is taken to be one of these. My philosophy thus escapes the ritual EPR sentence, "if, without in any way disturbing a system, we can predict with certainty. . . ." First, since the *AB* vector is taken to be spacelike, I must replace the word *predict* by *teledict*. And second, the *telediction* is also a *teleaction* – with the relaying satellite placed in the past.

Before explaining how relativistic covariance is preserved in all this I should speak of experimental verifications of my idea.

First, one could take as α and β two impartial, passive, observers. In this form the EPR experiment has been done many times, including those recently inspired by Shimony ([51]–[53]).

Second, one could take an impartial observer as β and a selected or trained psychokinetic agent as α. This would be an experiment in psychokinesis, with the observer looking not over the agent's shoulder (as usual), but along a lateral channel. It would certainly be an interesting experiment if performed with a sophisticated apparatus of the Shimony family.

Finally, one can take two trained psychokinetic agents as α and β, and have them either compete or cooperate. This would also be an interesting experiment.

As with relativistic covariance, there is 'no problem'. The measurements by α and β are both performed inside limited space–time domains, which can be thought of as extremely small with respect to the spacelike distance $r_A - r_b$ and to the time distance $t_A = t_B$. In fact we are working with propagators or relativistic Green's functions, attached to the two vectors OA and OB. Relativistic covariance is obvious.

7. WIGNER'S FRIEND

And what if two observers α and β look at the same recording apparatus O, which we take with Wigner [9] to be quantal, that is, not macroscopic in the sense of Ludwig [5], or of the Prosperi [54] group? The recorded measurement is transmitted, via information waves (say, electromagnetic waves) between O and both α and β. And, by the very hypothesis, both α and β are collapsing, strictly coupled states in the EPR sense. Thus what we have is akin to the EPR situation.

And what if we follow Wigner and insist that somebody, for instance α, describes the total system also after the measurement by β has been made? Moldauer ([3], [4]) has thoroughly discussed the technicalities of this problem. Operationally speaking, it is hard to conceive what sort of measuring apparatus would be able to test the phenomenology of the combined system. Looked at philosophically, however, the question makes sense and raises as a following question that of a hierarchy of superminds looking over each other's shoulders.

I will not delve into this near-to-metaphysical problem, but rather fall back on phenomenology and feasible experimentation. Observer β, after his measurement, is certainly no more in a linear superposition of states, until α finds out which is which, than Schrödinger's cat is before the biologist opens the box. Here, again, what we have is competition or cooperation between active psyches who are producing the state vector. In the Schrödinger problem it seems that the cat is more strongly motivated, and less indirectly coupled, to the decaying atom, so that his decision has *a priori* far more weight than that of the biologist. However, I do not exclude that some sort of telepathic experimentation between the cat and the biologist could make sense in Schrödinger's context. On the other hand, in the EPR context, the very symmetry postulated between the α and β (real or virtual) observers has led us to conceive a 'fair contest' between α and β, as if (*mutatis mutandis*) they were pulling the ends of a rope going over a pulley situated in the past. It seems to me that Wigner's problem lends itself to any specification between these two extreme cases. One thing is certain however, and Wigner states it quite clearly: No observer (neither cat nor experimentalist) can have his mind in a superposition of states, *because it is an act (either cognizance or will) of that mind that collapses the state vector*.

Now I am well aware that this leaves me with a very serious problem I must finally discuss.

8. WHAT IF THERE IS NO CAT IN SCHRÖDINGER'S BOX?

Let us recall the situation. We have ideally, say, one single β-radioactive atom enclosed in a little cell around point $\mathbf{r} = 0$ and time $t = 0$. Its half-life is much smaller than, say, T, so that, reasoning predictively, we feel confident that when we open the box at time T the atom has decayed. Now, the β electron may either trigger a Geiger counter seen through the solid angle Ω from point O, with *a priori* probability $\Omega/4\pi$, or else pass beside the Geiger counter with *a priori* probability $1 - \Omega/4\pi$. When triggering the counter, the quantal event induces a cascade and thus a macroscopic event in the sense of classical physics. However, the hypothesis now is that the recording apparatus is no longer a cat, but merely any physical recorder you like.

Nobody on earth, including von Neumann or London and Bauer, would have it that the die is cast at the end of time T. Time T may be, say, ten years, and the half-life of the atom 1 nsec. Such a belief is of course unprovable because, anyhow, somebody has to look at the recorder; and even if the recorder includes a recording clock, it could be logically maintained that the transition has been induced, via advanced waves, by the final look of the observer.

Thus it seems that the very consistency of the London-Bauer philosophy, which I have built into mine, implies that our world is full of rudimentary psyches which (as proved by the preponderance of retarded over advanced waves) are usually more passive than active, more of the sort of impartial observers than of energetic wills. However, the truly wonderful facts of both biological ontogenesis and phylogenesis may well suggest that at least some among these rudimentary psyches are more willingly inclined. I certainly need not recall that quite a few very eminent biologists, philosophers, or even mathematicians have made this sort of speculation; there are far more names here than just the two I have quoted ([27], [28]).

9. CONCLUDING REMARKS

Concluding, I agree with those distinguished physicists and/or philosophers of science who do not see, *inside* the quantal formalism, anything akin to the stochastic event that was postulated to occur in classical statistical mechanics. Therefore, with von Neumann and with London and Bauer, I feel that a special postulate is necessary for bringing into existence the *stochastic event*, or *transition*, which quantum mechanics certainly needs on experimental grounds. And I cannot see any other plausible way of doing this than by stating that the so-called *collapse of the state vector* occurs through an act of consciousness on the part of the observer.

Then, arguing from the philosophy of physical irreversibility that is today accepted by many thinkers, and from the corollary I believe should be drawn from intrinsic time symmetry to intrinsic symmetry between cognizance and will, I am led to conceive that the act of consiousness producing the quantal transition can be an act of will just as well as an act of cognizance; that is, the sink of an advanced wave just as well as the source of a retarded wave.

Finally, the need for consistency of the whole scheme leads me to think of the world we are living in as a Leibnitzian world, where cats are rather high in the hierarchy of monads.

Through the space-time vacuum quantal information waves ripple, with full relativistic covariance, from monad to monad, and they are *de jure* just as alive in their advanced interpretation as they are so obviously cascading in their retarded interpretation. Paraphrasing Bergson, I would say that advanced waves are rather dormant than absent.

Of course, I am well aware that, in proposing this high-brow sort of paradox, by referring to Leibnitz and to an updated version of the Loschmidt and Zermelo paradoxes, I am *ipso facto* letting in a paradox of the extreme low-brow, creeping sort: psychokinesis.

Let me summon Hippocrates as an attorney, because of his aphorism:[16] *Extreme remedies are the most appropriate for extreme diseases*. Fifty years of writing (more than once by competent and/or subtle thinkers) without having settled matters certainly proves that, notwithstanding its vigorous health, quantum mechanics suffers from an enigmatic illness and needs an appropriate operation. If the reader thinks the treatment I am offering is somewhat akin to acupuncture, please consider that Everett has seriously put forth something even more fantastic, and a theory which (as far as I can see) is not falsifiable. My theory, if admittedly less respectable when seen from below than when seen from above, is at least falsifiable.

Institut Henri Poincaré, Paris, France

NOTES

[1] The argument has been rediscovered independently by Abelé and Malvaux [15].

[2] Yilmaz points out that the Galilean group formula does not preserve orthogonality of light rays and wave planes *in ordinary space*. But this orthogonality is preserved by the relativity of simultaneity. Incidentally, a very similar argument answers Landé [56] when he states that the Einstein-de Broglie formula $\mathbf{p} = \hbar\mathbf{k}$ is not invariant under the Galileo transformation.

[3] Poincaré is the proponent of the four-dimensional interpretation of relativity, and Minkowski's inspirer.

[4] That the quantal formalism has *nothing* in itself to tell us that an individual event (or transition) occurs can be displayed in more than one way. Here is the simplest one. Consider the expansion of the state vector upon the orthogonal set ϕ_K characterizing a measurement process $\psi(x, t) = \Sigma c_K(c)\phi_K(x)$, where $|c_K|^2$ is the probability of finding the state ϕ_K. There is *nothing inside* the formalism implying that some sort of discontinuity exists and induces the transition. Thus most authors oppose the continuous or causal development of ψ, as governed by Schrödinger's equation, to the *discontinuous jump* that the 'collapse of the state vector' must be postulated to be.

[5] For an extensive bibliography see [23].

[6] It does not seem plausible that macroscopic physical irreversibility has its root in the rare and weak T-violating interactions that have been recently discovered. Moreover, contrary to Lee and Yang's C-violations, the T-violations are not yet well understood. It is possible that, after all, they fall in the general category of time asymmetry as governed by a boundary condition.

[7] To say that the $A \to B$ and the $B \to A$ transitions have the same predictive (intrinsic) probabilities is not identical to saying that the (intrinsic) predictive probability that A goes into B equals the (intrinsic) retrodictive probability that B has come from A. That these two sorts of reversibility should be equal is known as the *principle of detailed balance*. This principle holds in many cases, for instance, in the two that are quoted.

[8] For an extensive bibliography see [23].

[9] Cox [29] gives an extensive bibliography; see also the references in [21]–[23].

[10] One need not say that entropy is an increasing function of probability if, and only if, the basis of logarithms is larger than one.

[11] In fact 'Boltzmann's constant' k was defined by Planck in the same historic paper where he proposed his h constant.

[12] Such a distinction loses its objective testability if we are speaking of one individual, quantal transition. Then it has solipsistic significance only. Let us display the (explicitly covariant) mathematical formalism underlying the philosophical problem.

According to Dirac and to Landé the composition law of quantal probability amplitudes may be written as

$$\langle a \mid b \rangle \langle b \mid c \rangle \langle c \mid a' \rangle = \delta\,(a, b') \tag{1}$$

where δ denotes the Kronecker delta ($\delta = 1$ if $a = a'$; 0 otherwise), the three expressions $\langle 1 \rangle$ are probability amplitudes, and are such that

$$\langle a \mid b \rangle = \langle b \mid a \rangle^* \tag{2}$$

An appropriate summation or integration is implied by repeated symbols at each junction, such as $\mid b \rangle \langle b \mid$. In fact, these junctions are projection operators.

Let us take an example: $\langle x \mid x' \rangle$ may be the propagator, or relativistic Green's function, associated with the wave equation under consideration, and $\langle x \mid k \rangle = \langle k \mid x \rangle^*$ the function $\exp(ikx)$ on the mass shell, 0 otherwise; kx denotes the space-time scalar product of the point instant x and the 4-frequency (or propagation vector)k. This formula is 'manifestly covariant'. My book [36] displays quite a collection of covariant formulas of this sort, for reciprocal Fourier transforms, etc.

Formula (1) may of course be written as

$$\langle a \mid c \rangle = \langle a \mid b \rangle \langle b \mid c \rangle \tag{3}$$

and a combined use of formulas (1) and (3) yields

$$\langle a \mid b \rangle \langle b \mid a' \rangle = \langle a \mid c \rangle \langle c \mid a' \rangle = \delta\,(a, a') \tag{4}$$

that is, conservation of orthonormality as expressed by summation either over b or over c. This is true in particular if $b = x$ and $c = x'$, that is, if $\langle b \mid c \rangle$ is the propagator. Conservation of orthonormality thus occurs *modulo* that the wave equation is obeyed, and this is because, in this formalism, obedience to the wave equation is built into the very definition of all of the algorithms. For this I refer the reader to my book [36].

It should be noted that this automatic conservation of the norm and the orthogonality is due to the fact that the composition law (1) or (3) is for probability *amplitudes* and *not* for probabilities. This remark has a strongly Landéian flavor, and points toward very deep implications, in natural philosophy, of the highly specific probabilistic formalism of the quantum theory (which of course is a leitmotiv in this paper). It should also be obvious that the preceding formulas are completely symmetric with respect to past and future, that is, prediction and retrodiction.

[13] This point is also made by d'Espagnat ([7], p. 302).

[14] See [46], [47] (especially pp. 196–197), and [48].

[15] It thus seems that any operational hidden variable theory would be even more paradoxical than the accepted quantal formalism. This certainly echoes another famous contest between modelism and formalism, three quarters of a century ago.

[16] Reece [55] gives this quotation (p. 88). This review article contains numerous references.

REFERENCES

[1] Jauch J. M., 1968. *Foundations of Quantum Mechanics* (Reading, Mass.: Addison-Wesley).

[2] Krips, H. P., 1969. *Philosophy of Science* 36 145.

[3] Moldauer, P. A., *Phys. Rev. D* 5 (1972), 1028.

[4] Moldauer, P. A., *Found Phys.* 2 (1972), 41.

[5] Ludwig, G., 'The Measurement Process and an Axiomatic Foundation of Quantum Mechanics.' In *Foundations of Quantum Mechanics*, ed. by B. d'Espagnat, p. 287 (New York: Academic Press).

[6] Sharp, D., 1961. *Philosophy of Science* 28 225.

[7] d'Espagnat, B., 1971. *Conceptual Foundations of Quantum Mechanics* (Menlo Park: Benjamin).

[8] d'Espagnat, B., 1971. 'mésure et non-séparabilité.' In *Foundations of Quantum Mechanics*, ed. by B. d'Espagnat, p. 84 (New York: Academic Press).

[9] Wigner, E. P., 1971. 'The Subject of Our Discussions.' In *Foundations of Quantum Mechanics*, ed. by B. d'Espagnat, p. 14 (New York: Academic Press).

[10] Hooker, C. A., 1970. *Am. J. Phys.* 38 851.

[11] Hooker, C. A., 1971. *Philosophy of Science* 38 224.

[12] Hooker, C. A., 1971. *Philosophy of Science* 38 418.

[13] Hooker, C. A., 1973. 'The Nature of Quantum Mechanical Reality: Einstein versus Bohr.' In *Paradox and Paradigm*, ed. by R. G. Colodny (Pittsburgh: Univ. of Pittsburgh Press).

[14] Hadamard, J., 1930. *Cours' d'Analyse Professé à l'École Polytechnique*, Vol. 2, p. 385 (Hermann).

[15] Abelé J. and P. Malvaux, 1954. *Vitesse et Univers Relativiste* (Paris: Sedes).

[16] Yilmaz, H., 'Could Relativity Theory Have Been Discovered in 1728?' (mimeographed paper).

[17] Poincaré, H., 1906. 'Sur la dynamique de l'électron.' In *Rendiconti Circolo Matematico di Palermo* 21 129.

[18] Colodny, R. G. (ed.), 1973. *Paradox and Paradigm* (Pittsburgh: University of Pittsburgh Press).

[19] von Neumann, J., 1932. *Mathematische Grundlagen der Quantenmechanik* (Berlin: Springer).

[20] London F. and E. Bauer, 1939. *La Théorie de l'Observation en Mécanique Quantique* (Paris: Hermann).

[21] Costa de Beauregard, O., 1964. 'Irreversibility Problems.' In *Proceedings of the 1964 International Congress for Logic, Methodology and Philosophy of Science*, ed. by Y. Bar-Hillel, p. 313 (Amsterdam and New York: North-Holland).

[22] Costa de Beauregard, O., 1970. 'Is There a Paradox in the Theory of Time Asymmetry.' In *A Critical Review of Thermodynamics*, ed. by E. B. Stuart, B. Gal-Or, and A. J. Brainard, p. 461 (Baltimore: Mono Books Corp.).

[23] Costa de Beauregard, O., 1971. *Studium Generale* 24 10.

[24] Landé, A., 1965. *New Foundations of Quantum Mechanics* (Cambridge: Cambridge University Press).

[25] van der Waals, J. D., 1911. *Phys. Z.* 12 547.

[26] Gibbs, J. W., 1914. *Elementary Principles in Statistical Mechanics*, p. 150 (New Haven: Yale University Press).

[27] Bergson, H., 1907. *L'Évolution Créatrice* (Paris: Presses Universitaires de France).
[28] Fantappie, L., 1944. *Teoria Unitaria del Mondo Fisico e Biologico* (Rome: Humanitas Nova).
[29] Cox, R. T., 1961. *The Algebra of Probable Inference* (Baltimore: The Johns Hopkins Press).
[30] Brillouin, L., 1962. *Science and Information Theory*, p. 294 (New York: Academic Press).
[31] Fock, V., 1948. *DAN SSSR* 60 1157.
[32] Ritz W. and A. Einstein, 1909. *Phys. Z.* 10 323.
[33] Jaynes, E. T., 1957. *Phys. Rev.* 106 620; 108 171.
[34] Elsasser, W. M., 1937. *Phys. Rev.* 52 987.
[35] Riesz, M., 1946. '*Sur Certaines Notions Fondamentales en Théorie Quantique Relativiste.*' In Actes du Dixième Congrès des Mathématiciens Scandinaves (Copenhagen: Gjellerup).
[36] Costa de Beauregard, O., 1967. *Précis de Mécanique Quantique Relativiste* (Paris: Dunod).
[37] Wightman A. S. and S. S. Schweber, 1955. *Phys. Rev.* 98 812.
[38] Dirac, P. A. M., 1930, 1935, 1947. *The Principles of Quantum Mechanics* (Oxford: Clarendon Press).
[39] Schmidt, H., 1970. *J. Appl. Phys.* 41 462.
[40] Schmidt, H., 1970. *J. Parapsychol.* 34 175.
[41] Price, G. R. 1972. *Science* 175 359.
[42] Einstein, A., B. Podolsky, and N. Rosen, 1935. *Phys. Rev.* 47 777.
[43] Einstein, A., 1928. 'Electrons et Photons.' In *Rapports et discussions du 5e Conseil Solvay*, p. 253 (Paris: Gauthier Villars).
[44] Schrödinger, E., 1935. *Naturwiss.* 33 807, 823, 844.
[45] Renninger, M., 1963. *Phys. Z.* 136 251.
[46] Costa de Beauregard, O., 1965. *Dialectica* 19 280.
[47] Costa de Beauregard, O., 1960. *Dialectica* 22 187.
[48] Costa de Beauregard, O., 1970. 'Discussion on Temporal Asymmetry in Thermodynamics and Cosmology.' In *Proceedings of the International Conference on Thermodynamics*, ed. by P. T. Landsberg, p. 539 (London: Butterworths).
[49] Bohm, D., 1951. *Quantum Theory*, Ch. 22 (New York: Prentice Hall).
[50] Bell, J. S., 1965. *Physics* 1 195.
[51] Shimony, A., 1971. 'Experimental Test of Local Hidden-Variable Theories.' In *Foundations of Quantum Mechanics*, ed. by B. d'Espagnat, p. 182 (New York: Academic Press).
[52] Freedman, S. J. and J. Clauser, 1972. *Phys. Rev. Lett.* 28 938.
[53] Freedman, S. J., 1972. 'Experimental Test of Local Hidden Variable Theories,' Ph.D. Thesis, unpublished, and references therein.
[54] Prosperi, G. M., 1971. 'Macroscopic Physics and the Problem of Measurement in Quantum Mechanics.' In *Foundations of Physics*, ed. by B. d'Espagnat, p. 97 (New York: Academic Press).
[55] Reece, G., 1973. *Int. J. Theor. Phys.* 7 81.
[56] Landé, A., 1973. *Quantum Mechanics in a New Key*, p. 11 (New York: Exposition Press).