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On the Zigzagging Causility Model of EPR Correlations and on the Interpretation of Quantum Mechanics[1]

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Being formalized inside the S-matrix scheme, the zigzagging causility model of EPR correlations has full Lorentz and CPT invariance. EPR correlations, proper or reversed, and Wheeler's smoky dragon metaphor are respectively pictured in spacetime or in the momentum-energy space, as V-shaped, Λ-shaped, or C-shaped ABC zigzags, with a summation at B over virtual states $|B\rangle\langle B|$. An exact "correspondence" exists between the Born-Jordan-Dirac "wavelike" algebra of transition amplitudes and the 1774 Laplace algebra of conditional probabilities, where the intermediate summations $|B)(B|$ were over "real hidden states." While the latter used conditional (or transition) probabilities $(A|C)=(C|A)$, the former uses transition (or conditional) amplitudes $\langle A|C\rangle=\langle C|A\rangle^*$. The formal parrallelism breaks down at the level of interpretation because $(A|C)=|\langle A|C\rangle|^2$. CPT invariance implies the Fock and Watanabe principle that, in quantum mechanics, retarded (advanced) waves are used for prediction (retrodiction), an expression of which is $\langle\Psi|\,U\,|\Phi\rangle=\langle\Psi|\,U\Phi\rangle=\langle\Psi U|\,\Phi\rangle$, with $|\Phi\rangle$ denoting a preparation, $|\Psi\rangle$ a measurement, and U the evolution operator. The transformation $|\Psi\rangle=|U\Phi\rangle$ or $|\Phi\rangle=|U^{-1}\Psi\rangle$ exchanges the "preparation representation" and the "measurement representation" of a system and is ancillary in the formalization of the quantum chance game by the "wavelike algebra" of conditional amplitude. In 1935 EPR overlooked that a conditional amplitude $\langle A|C\rangle=\sum\langle A|B\rangle\langle B|C\rangle$ between the two distant measurements is at stake, and that only measurements actually performed do make sense. The reversibility $\langle A|C\rangle=\langle C|A\rangle^*$ implies that causality is CPT-invariant, or arrowless, at the microlevel. Arrowed causality is a macroscopic emergence, corollary to wave retardation and probability increase. Factlike irreversibility states repression, not suppression, of "blind statistical retrodiction"—that is, of "final cause."

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1. INTRODUCTION

The zigzagging causality model of the 1935 Einstein-Podolsky-Rosen[1] (EPR) correlations has extreme simplicity (the correlation is tied by the particles themselves,[2] no occult, unknown, direct coupling is suspected, and the quantum potential is not called upon). It has manifest Lorentz and CPT-invariance,[3,4] obvious quantum orthodoxy (its backbone is the 1926 Born[5] and Jordan[6] wavelike probability calculus), and computational efficacy (it yields directly the correlation formulas,[2,3] as experimentally tested). In all this there is no wonder, as it consists of a specific application of the S-matrix scheme.

Extreme computational simplicity has a counterpart: mind-stretching interpretational problems, which, however, belong to the very core of the understanding of relativistic quantum mechanics.

Both the continuity and the discontinuity aspects between the classical and the quantal calculus of probabilities will be better emphasized if we first have a retrospective look at Laplace's 1774 algebra of conditional probabilities and at Maxwell's and Boltzmann's theory of colliding molecules.

2. BOLTZMANN'S COLLIDING MOLECULES AND LAPLACE'S CONDITIONAL PROBABILITIES REVISITED

The (unnormalized) collision probability $|A)\cdot(C|$ of two molecules A and C (that is, the number of chances of a collision) is the product of three independent probabilities: their (symmetric) mutual cross section[3]

$$(A\,|\,C)=(C\,|\,A) \tag{L1}$$

and the occupation numbers $|A)=(A|$ and $(C|=|C)$ of the initial states (or, more generally, the expectation values of these):

$$|A)\cdot(C|=|A)(A\,|\,C)(C|=|C)(C\,|\,A)(A|=|C)\cdot(A| \tag{L2}$$

This is for prediction. The same formula holds for retrodiction ("blind statistical retrodiction," in Watanabe's[7] wording). Thus, with B denoting the collision, both the "dressed transition probability" $|A)\cdot(C|$ and the "naked transition probability $(A\,|\,C)$ are invariant with respect to Λ or V shapes of the ABC zigzag (either in spacetime or the momentum-energy space).

[3] The following "Laplacean" equations are numbered as (L1), (L2), etc... as they "correspond" à la Bohr to the Diracian equations (D1), (D2), etc... of the following Section.

Now, according to the Bose or Fermi quantum statistics, the same formula holds for a < or C shape of the ABC zigzag, $|A)$ then denoting the initial occupation number of the initial state and $(C|$ the final occupation number of the final state.

Both Laplace and Boltzmann (enlightened in this by Loschmidt) did accept the symmetry rule (L1) in cases involving a transition from an initial state A to a final state C, but neither of them extended such a symmetry in the form (L2). Laplace,[(8)] whose approach was "subjectivist," saw no "sufficient reason" for ascribing prior probabilities $(C|$ to his "effects" (this being an implicit statement that the "contingent future" is totally unknowable). Boltzmann,[(9)] whose approach was "objectivist," merely took notice that "blind statistical prediction" is physical while "blind statistical retrodiction" is not. Thus, with different motivations, both Laplace and Boltzmann were expressing a statement of *maximal physical irreversibility*, to which we will come back in Sec. 10. However, this common prescription of ignoring the prior probabilities of the later events (that is, of equating them among themselves) was intrinsically illogical for the following reason: Multiplication by $|A)$, the prior probability of the earlier event, implies "statistical indistinguishability," and, if so (in the case, for example, of statistical mechanics), there are $(C|$ ways in which a colliding molecule can reach the final state. Therefore multiplication by $(C|$ is a corollary to multiplication by $|A)$.

In other words, the two quantum statistics, of Bose and of Fermi, have an internal consistency previously lacking, the corollary of which is explicit past-future symmetry. One need not say that experimentation vindicates the quantum statistics, with $|A) \cdot (C| = 0, 1, 2, 3,...,$ for bosons, or $= 0, 1$ for fermions.

Finally, the collision or transition probability $|A) \cdot (C|$ of two molecules thus has topological invariance with respect to Λ, V, or C shapes of the ABC zigzag, either in spacetime or the momentum-energy space. This stems from the fact that behind the geometry there is a probability algebra, the one presented in Laplace's series of memoirs devoted to conditional probabilities.[(8)]

In his 1774 "memoir" opening the series, Laplace's basic assumption was principle (L1).[4] There $(A|C) = (C|A)$ denotes what I will call the *intrinsic conditional probability* of "A if C" or of "C if A". Let this be illustrated by an example.

A denoting the height and C the weight of a U.S. citizen, the total number of U.S. citizens having this height and this weight is a number

[4] See Jaynes,[(10)] formula A6, p. 216. The normalizing denominator in this formula stems from an approach slightly different from the one followed here.

$(A \mid C) = (C \mid A)$. If we refine the sampling by distinguishing mutually exclusive categories (say, men and women) we must introduce the proportions $|A)$ and $(C|$ of citizens having this height and this weight in the categories and therefore write formula (L2).

Laplace, having (casually) introduced this very useful concept of an intrinsic, reversible conditional probability, later discarded it[5] in favor of the two converse extrinsic conditional probabilities $|A|\, C)$ of "A if C" and $|C|\, A)$ of "C if A" that have been used ever since, writing, instead of (L2), the well-known formula

$$|A) \cdot (C| = |A|\, C)(C| = |C|\, A)(A| = |C) \cdot (A| \tag{L3}$$

for the *joint probability* $|A) \cdot (C|$ of A and C.

I call $|A|\, C)$ and $|C|\, A)$ *extrinsic conditional probabilities* because (compare formulas (L2) and (L3)) they contain the prior probabilities $|A)$ or $|C)$.

It obvious that

$$|A|\, C) \neq |C|\, A) \qquad \textit{iff} \quad (C| \neq |A) \tag{L4}$$

This is the basis of both Laplace's and Boltzmann's discussions of "factlike irreversibility" (Mehlberg's[(11)] wording). Van der Waals[(12)] explained the connection between the two approaches.

Maximal irreversibility occurs if, say, all $(C|$'s are equal among themselves, as assumed by both Laplace and Boltzmann for their "final states." But this is a much too radical and extreme statement of the factlike physical irreversibility.

Being an algebraic formula, (L4) expresses a timeless, logical sort of irreversibility. For example, as basketball players are usually tall and light, in this category $|A|\, C)$ is much larger than $|C|\, A)$ if A and C express large values of the height A and the weight C.

I have inserted a dot in the expression (L2) of $|A) \cdot (C|$ in analogy with a scalar product $A \cdot C = AC \cos \alpha$—and, indeed, $(A \mid C)$ "corresponds" to a cosine. Pursuing this analogy, we write $A \cdot A = AA$. Therefore, setting $C = A$ in (L2), we get

$$|A) \cdot (A| = |A)(A| = |A)(A \mid A)(A| \tag{L5}$$

showing that iff $(A \mid A) = 1$, $|A)(A|$ is idempotent. Thus follow three statements: the intrinsic conditional probability of A if A equals unity; the extrinsic conditional probability of A if A equals the prior probability of A; and the joint probability of A and A is idempotent.

[5] See Jaynes[(10)] formula A7, p. 216. Incidentically, the formula $|A|\, C) = |C|\, A)(A| : (C|$ is often called Bayes's formula.

Assuming that $(A \mid A) = 1$ allows orthonormalization of sets of mutually exclusive occurrences, according to

$$(A \mid A') = \delta(A, A') \tag{L6}$$

In analogy with the quantum paradigm, we then interpret formula (1) as a matrix transposition and call the sets $|A)$ "representations" of a system. We then notice that (intrinsic) conditional probability and transition probability are synonymous wordings for a basically algebraic, or timeless, concept. Previously we have encountered the $|A)$ and the $|C)$ representations of a colliding molecule, and the height and the weight representations of a U.S. citizen.

It often does make sense to express a conditional or transition probability $(A \mid C)$ with a summation over a complete set of intermediate states B, classically thought of as "real but hidden." For example, we write, for colliding molecules,

$$(A \mid C) = \sum (A \mid B)(B \mid C) \tag{L7}$$

B denoting the states of the pair while in contact; for spherical molecules, B then denotes the line of the centers. Thus, formula (L7) has topological invariance with respect to Λ, V, or C shapes of an ABC zigzag. The word "intermediate" is understood in the sense obvious in the formula, that is, *algebraically*, or topologically.

An other example is as follows: In a U.S. National Park, we may be interested in the joint probability $|A) \cdot (C|$, or the conditional probability $(A \mid C)$, that there is at A the male and at C the female of a couple of bears. Coupling means interaction; for example, the two bears can meet at some hidden intermediate place B.

It really makes no difference if the AC vector is spacelike, future timelike, or past timelike, and if B is in the common past or future of A and C or if it is after A and before C (or *vice versa*). This transition probability is between the male representation and the female representation of the bears. Again, logic, not timing, is at stake.

Formula (L7) is known as the generating formula of Markov chains. Due to the symmetry property (L1), the chain can zigzag arbitrarily throughout either spacetime or the momentum energy space, disregarding the macroscopic time or energy arrow.

A complete Markov chain is written as

$$|A) \cdot (L| = \sum \sum \cdots |A)(A \mid B)(B| \cdots |K)(K \mid L)(L| \tag{L8}$$

A leitmotif in the Bayesian approach is that the end prior probabilities are shorthand notations for conditional probabilities $(E \mid A)$ and $(L \mid E')$ linking the system to the environment. Thus we are left with essentially two basic concepts: the joint probability $|A)\cdot(C|$ here defined as an operator, and the intrinsic conditional or transition probability $(A|C)$.

This ends our tour of the room devoted to Laplace's conditional probabilities and Boltzmann's transition probabilities in the Probability Museum. The next room is devoted to the conditional or transition amplitudes of Born[5] and Jordan,[6] cast by Dirac[13] in the form of a "bra" and "ket" symbolic calculus.

The reader may have noticed that the new notations I have used for presenting Laplace's probability algebra are tailored so as to "correspond" to those introduced by Dirac for the Born-Jordan algebra, and, at the same stroke, to endow this algebra with a "manifest relativistic invariance."

3. THE WAVELIKE PROBABILITY ALGEBRA OF BORN, JORDAN, AND DIRAC

Being an essential contribution to Einstein's and de Broglie's wave-particle duality, the 1926 probability amplitude algebra of Born[5] and Jordan[6] bridges in its own style the gap between the continuous and the discrete. In Kuhn's wording, it is a "scientific revolution," replacing the traditional rules of addition of partial, and multiplication of independent probabilities, by analogous rules pertaining to amplitudes. In his *Principles of Quantum Mechanics*, Dirac[13] casts this scheme in the form of a "bra" and "ket" symbolic calculus, exactly "corresponding" to the Laplacean scheme summarized in the preceding section. However, although strictly parallel to each other, the two algebras are not superposable as far as interpretation is concerned. From this stem the thousand and one "paradoxes" of quantum mechanics, the thousand-and-first one being the "EPR paradox" discussed in Sec. 4 and 8.

"Corresponding" to Laplace's symmetry assumption (L1), there is, in the Born-Jordan-Dirac algebra, the Hermitean symmetry

$$\langle A|C\rangle = \langle C|A\rangle^* \tag{D1}$$

interpreted as matrix conjugation. "Corresponding" to the expression (L2) of a joint probability, there is that of a joint amplitude

$$|A\rangle\cdot\langle C| = |A\rangle\langle A|C\rangle\langle C| \tag{D2}$$

as a product of three independent amplitudes: an intrinsic conditional or transition amplitude (D1), and two prior amplitudes, the absolute squares of which are occupation numbers (or, more generally, the expectation values of these).

Setting $C = A$ in (D2), we see that, iff $\langle A \mid A \rangle = 1$, then $|A\rangle \cdot \langle A| = |A\rangle\langle A|$ is a projector. Orthonormalization of a representation is then allowed according to

$$\langle A \mid A' \rangle = \delta(A, A') \tag{D6}$$

It is often useful to express a conditional or transition amplitude with a summation over a complete set of intermediate states, according to

$$\langle A \mid C \rangle = \sum \langle A \mid B \rangle \langle B \mid C \rangle \tag{D7}$$

The word "intermediate" is understood in the (obvious) algebraic sense displayed in the formula or, whenever a spacetime or a momentum-energy connotation is attached to the occurrences *A*, *B*, etc. in a topological sense. In that latter case, the amplitudes $\langle A \mid B \rangle$ etc. are termed (Feynman) propagators.

Formula (D7) is known as the generating formula of Landé[14] chains.

Due to the symmetry property (D1), a Landé chain can zigzag arbitrarily throughout either spacetime or the momentum-energy space, disregarding the macroscopic time or energy arrow.

A complete Landé chain has the form

$$|A\rangle \cdot \langle L| = \sum \sum \dots |A\rangle\langle A \mid B \rangle\langle B| \dots |K\rangle\langle K\rangle\langle L| \tag{D8}$$

End prior amplitudes such as $|A\rangle$ and $\langle L|$ are shorthand notations for conditional amplitudes $\langle E|A\rangle$ and $\langle L \mid E'\rangle$ connecting the system to the environment. Dirac[13] uses this concept in the form $\langle x \mid A\rangle$ or $\langle k \mid A \rangle$ in the spacetime or the momentum-energy pictures, respectively.

An important generalization of Landé chains consists of the Feynman[15] graphs, where more than two links $\langle A \mid B \rangle$ can be attached to any vertex *A*. Topological invariance is a well-known property of Feynman graphs.

It is also well known that the overall transition amplitude $\langle \Psi | \Phi \rangle$ between a set of preparations $|\varphi\rangle$ and a set of measurements $|\psi\rangle$, where $|\Phi\rangle = \pi\, |\varphi\rangle$ and $|\Psi\rangle = \pi\, |\psi\rangle$, is a *conditional amplitude holding if and only if each and every of the preparations* $|\varphi\rangle$ *and of the measurements* $|\psi\rangle$, *as written down in the formula, is performed.* Nonobservance of this "caveat" has caused some very serious misinterpretations of the EPR correlations, as I have explained.[16]

Last (but not least) comes the well-known formula deriving the quantum transition or conditional probability from the corresponding amplitude:

$$(A \mid C) = |\langle A \mid C \rangle|^2 \tag{D9}$$

The presence of cross terms in the squared amplitude abrogates *ipso facto* the classical rules pertaining to partial, and independent, probabilities, thus entailing the typically quantum phenomenon termed, algebraically, "nonseparability," and, geometrically, "nonlocality." For this very reason, the intermediate summation $|B\rangle\langle B|$ in formula (D7) can *not* be understood as implying "real hidden states," and is thus said to be over "virtual states."

Of course, use of an "adapted representation" formally suppresses the cross terms in formula (D9). But this is no more than a sort of perspective effect, like displaying a parallelepiped in the form of a rectangle by viewing it "normally."

A basic rule in the quantum game is that to a physical measurement corresponds an adapted representation, displaying its results in a classical form (and excluding simultaneous measurement of some other magnitudes). The quantum rule then states: "Forget the concealed phase relations and proceed to the next measurement." This is much like cutting the Gordian knot. So Bergson[17] may be very right in writing that we, "Homo sapiens," are more truly a "Homo faber," using his knife at practical ends.

Quantum preparations and measurements thus are like stepping stones resting upon what we think is our "real macroscopic world." Cutting away the phase relations, by using formula (D9), abolishes the stream that is stepped over. But, of course, *this is an approximation*, disregarding the quantum subtleties. In principle, the phase relations can be recovered by including the preparing and measuring devices in the description (often with great difficulty, both conceptual and experimental). Many needles get lost in haystacks when the scenery is enlarged!

Among other things, quantum physics has taught us that the macroscopic approximation just mentioned is *not* the picture of a "real world," but rather the expression of a selected daydream common to a subclass of onlookers, a "maya" sort of world, where selected intersubjectivity replaces objectivity. Jung's concept of a "collective unconscious" may have relevance here.

4. THE BASIC TRIVIUM: WHEELER'S SMOKY DRAGON AND EPR CORRELATIONS (PROPER AND REVERSED)

In what state is a quantum system evolving from its preparation as $|A\rangle$ and its measurement as $|C\rangle$? Is it in the retarded state, the source of which is $|A\rangle$ (as one familiar with macrophysics is used to think)? Or is it in the advanced state, the sink of which is $|C\rangle$, as is equally acceptable due to the symmery property (D1)? It cannot be in both if there is a transition;

but then, why in the one rather than in the other? The truth is that *it is neither in the one nor in the other, because it is actually transiting* from the one to the other. Therefore it is expressible, via formula (D7), as a superposition of products of virtual states $|B\rangle\langle B|$. Miller and Wheeler[18] liken it to a "smoky dragon," living, so to speak, above our empirical spacetime, where only dwell its "tail" held as $|A\rangle$ and its "mouth" biting as $|C\rangle$. The much used concept of an "evolving state vector" $|\psi(t)\rangle$ is thus useless, being untestable; worse, being misleading, and causing spurious difficulties with Lorentz-invariance[19] and CPT invariance.[20] *Only the transition amplitude $\langle A|C\rangle$ between preparation and measurement does make sense.*

So much for the C shape of an ABC zigzag.

The V-shape illustrates what is called an EPR correlation, where, from a common source B, two subsystems measured at distant places A and C emerge. A Λ-shaped ABC zigzag illustrates a reversed EPR correlation, where two distant preparations at A and C merge into a common sink B. In either case there is at B only a "smoky dragon," a superposition $|B\rangle\langle B|$ of products of virtual states. *In this consists the so-called "EPR paradox."* No corrresponding paradox exists in the case of a classical correlation, where the superposition $|B)(B|$ is over "real hidden states." That the EPR dragon proper has two biting mouths, and the reversed EPR dragon two tails at A and C but no body at B, well suits a smoky dragon.

It is helpful to visualize that at the vertex B is attached a third (real, or ideal) particle B. Thus, for a classical, Boltzmannian collision, we rewrite formula (L7) in the form

$$(A|C)=\sum(B|A)(B|C) \overset{\text{def}}{=} (B|A)\,|C) \tag{L10}$$

and, for a quantal transition, we rewrite formula (D7) in the form

$$\langle A|C\rangle=\sum\langle B|A\rangle^*\langle B|C\rangle \overset{\text{def}}{=} \langle B|A\rangle\,|C\rangle \tag{D10}$$

In the case of a C-shaped ABC zigzag, we can thus ideally liken the preparing-and-measuring device to a virtual particle intruding at B. Also, we can think of an EPR pair of particles as issuing from the disintegration of a particle $|B\rangle$ (EPR correlation proper), or as synthetizing a particle $|B\rangle$ (reversed EPR correlation). Thus we interpret the summation $|B\rangle\langle B|$ as an equivalent pure state, but one belonging to the $A\otimes C$ Hilbert space. The body of the dragon is not in the same world as its tail and mouth. Of course, the classical mixture $|B)(B|$ of "real hidden states" had less mind-stretching overtones.

5. CPT-INVARIANCE AS THE LEGAL HEIR OF LOSCHMIDT'S TIME REVERSAL INVARIANCE

A basic principle in the second-quantized algebra is that a "ket" expresses either emission of an antiparticle or absorption of a particle, and conversely for a "bra." Therefore we can agree that starring a scalar product $\langle A|B\rangle$, or antistarring $\langle A|B\rangle^*$, expresses particle-antiparticle exchange, denoted as C; and that exchanging the labels inside $\langle A|B\rangle$ expresses preparation-measurement exchange, or emission-absorption exchange, denoted as PT (Racah's[21] spacetime reversal). Thus, whenever a spacetime or a momentum-energy connotation is attached to the occurrences $A, B, \ldots$ *the Hermitian symmetry law* (D1) *expresses* CPT *invariance.* The bra $\langle|$ and ket $|\rangle$ arrows then are in a one-to-one association with Feynman's arrows symbolizing particles and antiparticles. This can be neatly formalized as:

$$\text{C:} \qquad \langle A|B\rangle \rightleftharpoons \langle A|B\rangle^*$$

$$\text{PT:} \qquad \langle A|B\rangle \rightleftharpoons \langle B|A\rangle$$

$$\text{CPT}=1: \qquad \langle A|B\rangle = \langle B|A\rangle^*$$

Lüders[22] 1952 geometric "strong reflection," here denoted as $\Pi\Theta$, has two effects: *covariant motion reversal* PT *and particle-antiparticle exchange,* denoted as C. Thus

$$\Pi\Theta = \text{CPT} = 1$$

Borrowing from the relativistic jargon, we can say that covariant motion reversal and particle-antiparticle exchange are two "relative images" of essentially the same operation.

CPT invariance entails the law of detailed balance

$$A + \bar{B} + \ldots \rightleftharpoons C + \bar{D} + \ldots$$

where a bar means particle on the left-hand side and antiparticle on the right-hand side (and conversely for nonbar).

It is thus clear that CPT *invariance is the legal, quantum-and relativistic, heir of Loschmidt's*[23] *time reversal invariance.* This should never be forgotten[24] when discussing the physical lawlike reversibility and factlike irreversibility.

6. PREDICTION-RETRODICTION SYMMETRY, RETARDED-ADVANCED WAVE SYMMETRY, AND THE QUANTUM CHANCE GAME

In the covariant Schwinger[25] interaction picture, the transition amplitude $\langle \Psi | \Phi \rangle$ between an overall preparation $|\Phi\rangle = \Pi |\varphi\rangle$ and an overall measurement $|\Psi\rangle = \Pi |\psi\rangle$ can assume three equivalent forms:

$$\langle \Psi | U\Phi \rangle = \langle \Psi U | \Phi \rangle = \langle \Psi | U | \Phi \rangle. \tag{1}$$

The first one, projecting the retarded preparation unto the measurement, is called "state vector collapse," and is appropriate for prediction. The second one, projecting the advanced measurement unto the preparation, is appropriate for retrodiction ("blind statistical retrodiction," in Watanabe's[7] wording); let us call it "retrocollapse." The third one expresses a symmetric "collapse-and-retrocollapse" concept. All three concepts merely are thinking and computational aids, devoid of any realistic physical interpretation.

The first equality (1) concisely expresses Fock's[26] 1948 and Watanabe's[7] 1955 principle that, in quantum mechanics, retarted waves are used in prediction and advanced waves in retrodiction—a statement implied also in J. von Neumann's[27] quantum version of the H-theorem. Incidentally, this settles a famous Ritz-Einstein[28] controversy, where reciprocal rather than contradictory assumptions were used by the contendants.

Remembering the content of the preceding section, we state that, in quantum mechanics, *the prediction-retrodiction symmetry is equivalent to the* CPT,[24] *not to the* PT-*symmetry.*

Formulas $|\Psi\rangle = |U\Phi\rangle$ and $|\Phi\rangle = |U^{-1}\Psi\rangle$ exchange the "preparation representation" and the "measurement representation" of a physical system. What they afford merely is a time-laden dramatization of the Born-Jordan wavelike algebra, somewhat like the Greek tragedy dramatized the fate philosophy.

Contrary to those believing[29] that the "state vector" collapse is "added by hand" to the fundamental "deterministic evolution" of a system, I submit that *what makes the essence of quantum mechanics is the chance game of questions and answers obeying the Born-Jordan-Dirac algebra*, and that what is ancillary is the "evolution in time" connecting these, in the manner of a computer's network. Thus the quantum sequence *preparation-evolution-measurement* "corresponds" to the cybernetic sequence *coding-transmitting-decoding.*

Therefore, what lies at the heart of both the classical $(A \mid C) = (C \mid A)$ and the quantal $\langle A \mid C \rangle = \langle C \mid A \rangle^*$ symmetries is the *lawlike reversibility*

$$\textit{negentropy} \rightleftharpoons \textit{information} \tag{2}$$

rediscovered in cybernetics, but known since long ago by philosophers as the *twin-faced information concept*: gain in knowledge, organizing power. Why the one face is so conspicuous, and the other so much "hidden," is of course the "factlike irreversibility law." This law does *not* state suppression, but does state (strong) *repression* of probability decreasing evolutions and of advanced waves propagations. According to factlike irreversibility, the upper arrow prevails over the lower one in (2). To use Aristotle's wording, "efficient cause" outweighs "final cause."

7. CAUSALITY AS IDENTIFIED WITH THE CONDITIONAL PROBABILITY OR (STILL BETTER) THE CONDITIONAL AMPLITUDE CONCEPT: OPERATIONAL ARROWLESS CAUSALITY

Algebraically speaking, the causality concept is timeless. Logical implication is a form of causality, and it is timeless.

When timing is involved, is there anything more operational than "If you do this, then the probability that that will happen is..."; or: "If you find that, then the probability that this has occurred is..."? Is this not the very *operational definition of causality*, one binding the causality and the conditional probability concepts, and thus linking the objective and the subjective aspects of the information concept?

So, *causality does have lawlike* CPT *invariance, and is thus arrowless at the microlevel.* Arrowed causality is a macroscopic emergence—just one aspect of factlike irreversibility among others.

"Impossible to see in the future and to act in the past" is a much too radical statement of physical irreversibility. A taboo is not an impossibility. Observing and producing antiparticles was a taboo that has been trespassed. Similarly, "psychokinesis" and "precognition" (two wordings for essentially one phenomenon) are quite rational implications of the formalism; it should be no surprise that they have been experimentally demonstrated by various authors. Let it be emphasized that psychokinesis essentially is retropsychokinesis: Influencing falling dice must operate before the outcome is displayed. *Occurrence of psychokinetic and/or precognitive phenomena is and unavoidable corollary of the reversibility laws* (L1), (D1) and (2).

Softening the irreversibility law in any of its too radical forms implies that the prior probabilities $(C|$ of the final states are not necessarily equal among thenselves. Ascribing values to them, or controlling them (if only to a small extent) expresses respectively precognition or psychokinesis.

One point needs be made here in view of the following: Use of psychokinesis together with V shaped ABC zigzags (either classical or quantum) should allow faster-than-light and backwards-in-time-telegraphing. But, conversely, no such telegraphing (neither classical nor quantum) is possible without recourse to psychokinesis. This should settle some "wild" claims that have been made in connection with the EPR correlations.

Suppose we have at B a "random event generator" sending (by definition) identical signals on two diverging lines BA and BC; an "agent" influencing the outcome at A will "retroact" upon the source at B, so that, by biasing the issue at A, he will similarly bias it at C. Thus, if the AC separation is spacelike, he will "telegraph faster than light"; and, if it is past timelike, he will "telegraph backwards in time." Such an experiment would be no more difficult than those already performed in psychokinesis.

8. BACK TO THE BASIC TRIVIUM: ULTRAFAST DERIVATION OF EPR CORRELATION FORMULAS

8.1. EPRB[38] correlation of linearly polarized photons

E and **H** denoting the electric and magnetic fields, a spin zero pair of photons A and C issuing from, say, an atomic cascade necessarily has[3] one of the two Lorentz invariant and, CPT invariant forms

$$\mathbf{E}_A \cdot \mathbf{E}_C - \mathbf{H}_A \cdot \mathbf{H}_C \qquad \textit{or} \qquad \mathbf{E}_A \cdot \mathbf{H}_C + \mathbf{H}_A \cdot \mathbf{E}_C \tag{3}$$

the symmetry of which in A and C is conspicuous. Let us call them the "type 1" and "type 2" amplitudes.

In an experimental arrangement such that the photons fly in opposite directions and denoting by α the angle between $\mathbf{E}_A$ and $\mathbf{E}_C$ (that is also between $\mathbf{H}_A$ and $-\mathbf{H}_C$) and normalizing, we get the conditional amplitude

$$\langle A \mid C \rangle = (1/\sqrt{2}) \cos \alpha \qquad \text{or} \qquad (1/\sqrt{2}) \sin \alpha \tag{4}$$

which has been experimentally tested.[32]

8.2. EPRB[38] correlation of a fermion-antifermion spin zero pair

Denoting $\bar{\varphi}$ and ψ Dirac spinors, the spin zero electron $\bar{\varphi}$-positron ψ pair issuing from, say, the disintegration of positronium necessarily has one of the two Lorentz-invariant forms $\bar{\varphi}\psi$ or $\bar{\varphi}\gamma_5\psi$. In the rest frame of the pair, where the two particles fly with opposite velocities $\pm c\beta$, one finds,[16] after some algebra,

$$\bar{\varphi}\psi = sero\ times(\uparrow\downarrow + \downarrow\uparrow),\ \bar{\varphi}\gamma_5\psi = (1-\beta^2)^{1/2}[\uparrow\downarrow - \downarrow\uparrow] \tag{5}$$

Comment:

(1) Only the antisymmetric spin state shows up.

(2) The conditional amplitude $\langle A \mid C \rangle$ has geometric and relativistic invariance; it is independent of the angle between the (opposite) momenta and (opposite) eigenvalued spins.

(3) In the extreme relativistic limit, $\beta^2 \to 1$, where this angle is known to go to zero, the particle and antiparticle have opposite pure helicity states.

(4) As, α denoting the arbitrary angle between the axes chosen for measuring the spins at A and C, the conditional probability $(A \mid C)$ has the expressions

$$\begin{aligned} (+\mid-) &= (-\mid+) = \tfrac{1}{4}(1+\cos\alpha) \\ (+\mid+) &= (-\mid-) = \tfrac{1}{4}(1-\cos\alpha) \end{aligned} \tag{6}$$

"angular momentum is not conserved," meaning that it is a magnitude shared between the pair and the measuring device.

8.3. EPR correlation proper between photons

In the original EPR *gedanken* experiment, the pair of particles A and C considered was in a momentum $p_A + p_C = 0$ and a position $r_A - r_C =$ const. eigenstate. We consider the conditional amplitude

$$\langle A \mid C \rangle = \langle r \mid p \rangle = \hbar \langle r \mid k \rangle \tag{7}$$

of finding the values r for the position of A and p for the momentum of C.

At this end we imagine[33] that a positronium atom disintegrates at B into two photons A and C, between a Heisenberg[34] 1927 microscope and a von Weizsäcker[35] 1931 microscope, pointing straight at each other along an axis x. A and C denoting the pointlike impacts of both photons in the image planes of the microscopes, the conditional amplitude $\langle A \mid C \rangle$ has the expression (7), where $\langle r \mid k \rangle$ denotes the Fourier nucleus. Thus, as retrodicted at B from the impacts at A and C (backwards through the microscopes), the position r and momentum p of the disintegrating positronium atom are subject to the Heisenberg uncertainty. This is compatible with the sharp impacts at A and C because retrodiction through the microscopes causes at B two diffraction patterns.

8.4. Discussion

No derivation of EPR correlations can be faster than the preceding ones. Based as they are on the S-matrix scheme, they have a built-in Lorentz-and-Lüders invariance. Therefore (and contrary to quite a few statements that have been issued) the phenomenon of EPR correlations, far from lacking any sort of relativistic invariance, does have an invariance much stronger than the simple Lorentz invariance.

The correlation formula also has invariance with respect to arbitrary displacements of the measuring devices along the beams of the two particles. Thus it is insensitive to the independent timings of the two measurements. This has been tested in a few experiments (including one by Aspect *et al.*[32]). Omnès,[36] after others, has commented upon this but without emphasizing the important point I come to now.

While those properties of V-shaped quantum correlations we have just considered are shared by the classical V-shaped correlations, there is, again, an essential difference between the two cases: While the classical summation $|B)(B|$ at the source B could be thought of as being over "paired real states," this is no more possible with the quantal summation $|B\rangle\langle B|$. Therefore, the magnitudes $|A\rangle$ and $|C\rangle$ arbitrarily chosen for measurements at A and C do not preexist in the source B, where only a "smoky dragon" is coiled.

Arbitrarily adjustable parameters exist at A and C (*e.g.*, turning linear polarizers, focusing a microscope either *à la* Heisenberg or *à la* Weizsäcker) but not at B. If causality has any operational meaning, it implies that something can be arbitrarily adjusted where and when the "cause" operates, and where and when the "effect" is tested. Thus cause and effect are tested at A and C, not at B. But, as the link of the correlation is proved (both theoretically and experimentally) to be the ABC zigzag, with a relay at B, the inevitable conclusion to be drawn from the EPR phenomenology is that *causality is arrowless at the microlevel.* This was true also with classical correlations, but the proof is much more vivid with the quantal correlations.

What counts in EPR correlations (and with the S-matrix scheme in general) is the setting of the preparing and measuring devices A and C while the particles do cross them. That what they are before is irrelevant has been tested by Aspect *et al.*[37]—a vivid and direct proof of advanced causality. By contrast, a reversed EPR correlation, displaying the familiar retarded aspect of causality, looks quite trivial.

What then of the C-shaped ABC zigzag, in the case of linearly polarized photons? Formulas (4) hold for a beam of photons crossing in succession two birefringent crystals A and C of relative orientation α. Nothing is changed by inserting a third birefringent crystal B, the length of which is such that a zero phase shift (modulo $2n\pi$) is introduced; this crystal B can be arbitrarily rotated. As there is no means to know upon which of the two beams it travels inside the crystal B, the photon there is a "smoky dragon."

To this we will come back in the Appendix.

9. CRITICAL EXAMINATION OF EPR'S 1935 ASSUMPTIONS

EPR[1] wrote: "*If, without in any way disturbing a system, we can predict with certainty... the value of a... quantity... then there exists a* [corresponding] *physical reality*" (their italics). This certainly looks like plain common sense. The fact is, however, that, by using an EPRB[38] model of correlations rather than the original EPR[1] model, the physical validity of EPR's assumptions can be definitely disproved.

To begin with, the word "predict" is quite infelicitous. As the original EPR model,[1] pertaining to positions or momenta, is formalized in the nonrelativistic quantum mechanics, the two distant measurements are treated as simultaneous—and must be so, because of the spreading of wave packets. Therefore "telediction" would be the appropriate word.

In the EPRB models, where the correlation is between spins or polarizations regardless of position or momentum, timing is irrelevant. Therefore, even in the nonrelativistic formalism, *the two measurements need not be simultaneous,*[39] and so the "telediction" can be also *either a prediction or a retrodiction.*

If one works with a relativistic formalism, such as the S-matrix scheme, the separation between the measurements can be either spacelike (as is usually the case), or past or future timelike.[40,41]

As applied to an EPRB[38] correlation, for example, between linear polarizations of a "type 1" spin-zero photon pair, EPR's[1] argument amounts to this: Finding at A the polarization $|A\rangle$ implies that at C the polarization is $|C\rangle = |A\rangle$, whereas, of course, symmetrically, finding $|C\rangle$ at C would imply that at A the polarization is $|C\rangle = |A\rangle$. But this is contrary to facts, because we *can* perform at A and C measurements with arbitrarily chosen directions, and then find (by repeating the test) that pairs of answers "yes" do turn out, with the frequency $\frac{1}{2}\cos^2\alpha$ (α denoting the angle between $|A\rangle$ and $|C\rangle$). Therefore, it is simply wrong that what is found at A (or C) fixes what "exists" at C (or A). The truth is that $(A|C)$ *is a conditional probability, holding if and only if both measurements are performed.* In today's jargon, "counterfactual thinking" is essentially incompatible with quantum mechanics.

Such a clear-cut refutation was, however, not possible by working with EPR's original model; in it, measuring as x_A the position of particle A implies that, *if measured,* the position of particle B is found as $x_B = x_A + \text{const.}$, whereas measuring as p_B the momentum of particle B implies that, *if measured,* the momentum of particle A is found as $p_A = -p_B$. In strict logic, one could then argue that, by measuring exactly x_A and p_B, one would know exactly both x_A and p_A, p_B and x_B, x_A and p_B directly, p_A and x_B indirectly. Thus, Heisenberg's uncertainties would be circumvented; they would be conceived as limiting the experimental knowledge available "here and there," but not the sharpness of a "hidden underlying reality."

Arguing that way is quite similar to an often recurrent (although quantally heretical) consideration pertaining to measurements succeeding each other in time. If, for example, a measurement $|C\rangle$ succeeds a preparation $|A\rangle$, with $|\langle A|C\rangle|^2 < 1$, it has more than once been argued[6] that the prepared system is then "known" to possess both magnitudes $|A\rangle$ and $|C\rangle$: the first one as directly measured, the second one as retroactively ascribed from the later measurement.

The phlogiston and the luminiferous ether also were "hidden realities" alien to an operational formalism, and have not survived.

To clinch our refutation of EPR's 1935 assumptions, we can remark[(43)] that one measurement at A is definitely not equivalent to two measurements, one at A and one at C. Representing two strictly correlated dichotomic magnitudes by matrices $Z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$, indexed A and C, and using the unit matrix $I = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$, the matrices $Z_A \otimes I_B$ and $I_A \otimes Z_B$ differ from each other, and from their half sum.

Last but not least, EPR's "no disturbance assumption" turns out, on closer examination, to be oversimplified. It is of course true that, in a classical V-shaped ABC correlation, a result $|A)$ found at A allows a strict telediction of what exists at C; this, with "no disturbance," because the measurement yields what existed as such in the source. That is no more true with the quantum correlation. Therefore there *is* indeed some subtle

[6] A fairly recent avatar of this often-manifested antiquantum heresy is found in a paper by Albert, Aharonov, and d'Amato,[(42)] a discussion of which is given below, in Appendix 1.

sort of "teleaction" from A to C—or between A and C, if both measurements are performed.

As emphasized by Shimony[44] and others, this amounts to "peaceful coexistence" between quantum mechanics and the 1905 relativity theory, where the "orthochronous" Lorentz invariance was shared by probability increasing evolutions, retarded waves, and arrowed causality. However, when viewed from the standpoint of the much stronger 1952 Lorentz-and-Lüders[22] invariance, there is hardly any doubt that the quantal non-separability must extend, in some way, to the states of mind of observers at A and C.

10. MACRORELATIVITY AND MICRORELATIVITY

Invariance of physical laws under "rotations" of the Poincaré-Minkowski tetrapod is the object of the 1905 relativity theory. "Factlike irreversibility," manifested as entropy or probability increase, wave retardation, and arrowed causality, shares this "orthochronous Lorentz invariance." Let us then call "macrorelativity" the theory stating *jointly Lorentz invariance and factlike irreversibility*.

Relativistic quantum mechanics is endowed with the much stronger Lorentz-and-Lüders invariance, according to which conditional probability is reversible, retarded and advanced waves are exchangeable, and causality is arrowless. Let us call this theory "microrelativity," stating *Lorentz-and-Lüders invariance.*

In 1927, at the Fifth Solvay Council, Einstein[45] pointed to a *sui generis* sort of distant correlation[7] implied in the "new quantum mechanics," mentioning rightly that it is incompatible with his 1905 relativity theory. Other physicists, including d'Espagnat,[46] later made analogous statements. Finally there emerged a consensus expressed by Shimony,[44] according to which there is "peaceful coexistence" between the two superpowers of macrorelativity and quantum mechanics, in the sense that physical irreversibility (taken as radical) drowns the grumbling.

All this, in my opinion,[3,4,33] is beating about the bush, because, as shown in Sec. 8, *the Einstein sort of correlations does have the full Lorentz and CPT invariance* inherent in relativistic quantum mechanics. Inner peace, not peacefull coexistence, is then the right word.

[7] The correlation then discussed by Einstein pertained to the impact at A and the nonimpact at C of one single particle carried by a wave diffracted at B.

11. EXTENDED STACETIME AND PROBABILITY

As there is only one world history, the frequency conception of probability is, strictly speaking, not acceptable in connection with "manifestly covariant" formalisms. Therefore, in matters fundamental, the original "subjectivist" conception of probability held by Bernouilli, Bayes, Laplace, and today advocated by Jaynes,[10] is the one to be used in connection with relativistically covariant formalisms.

Of course, repetition of a stochastic test, and, therefore, recourse to the frequency aspect of probability, are current practice. At CERN, for example, Feynman graphs are used in this way. This, however, is an approximation, to be discussed later.

Quite often the classical calculus of probabilities is used in problems where no timing is implied—as we have seen, for instance, in Sec. 2. Here is one more example: In the well known balls-in-boxes problem, we have balls and boxes differing among themselves only by their colors. All the balls are in the boxes. $|A)$ being the number of balls of color A and $(C|$ that of boxes of color C, the rule of the game is that all C boxes contain the same number $|A|\,C) = |A)(A\,|\,C)$ of A balls. Then, if one ball from one box is randomly picked, the "joint number of chances" of hitting a C box and an A ball is $|A)(A\,|\,C)(C|$. This is either the predictive probability of picking, or the retrodictive probability of having picked, an A ball from a C box. No timing, however, is really involved: the occupation numbers $|A)$ and $(C|$ and the intrinsic transition probability $(A\,|\,C)$ are "all there, present in space."

An other example, and one "corresponding" more closely to the S-matrix scheme, is that of phone booths A, B,... connected two by two. Then, the traffic $|A)\cdot(C|$ on a line is the product of three independent numbers: the channel capacity $(A\,|\,C)$ and the occupation rates of the two booths considered. Again, all three numbers "are there, in space."

Mutatis mutandis, this is how Feynman graphs are used. Both the Bose and the Fermi quantum statistics, used in connection with them, do imply that the initial occupation numbers of the initial states and the final occupation numbers of the final states "are there, in spacetime."

Can examples be produced where ascribing prior probabilities to the final states makes sense at the macroscopic level? Certainly! Here is one:

In the Darwinian line leading to the horse, there is the "eohippus." Given the eohippus, can we predict the horse? Of course not. But we can retrodict the primeval molecular soup (or an equivalent of it) by using in reverse the common Laplace and Boltzmann prescription; that is, equating among themselves the prior probabilities of the earlier states.

Although this is perfectly logical and legitimate, some will argue that the problem has thus been oversimplified, and that enlarging the context would reveal the Nicolis-Prigogine[47] phenomenology of out-of-equilibrium systems, producing order by feeding upon the universal negentropy cascade. That is very true. But it is no less true that changing the data of a problem entails a change in the assignment of prior probabilities.

An other objection to be expected is that, after all, the eohippus was not so improbable, as the skeleton of one is displayed in New York. But that is a sophism: Ascribing the prior probability of a later event is "blind statistical retrodiction," or finalistic reasoning, the very thing that the argument was intended to set aside!

Again, probability has to do fundamentally with logic, and only occasionally with timing. Then (using Aristotle's wording) it expresses "efficient cause" when used predictively, and "final cause" when used retrodictively. And there are definitely cases (we have just seen one) where "final cause" does make sense.

Final causation is sometimes called retrocausation, but this is a very misleading wording,[24] implying something like "propagation in time," which of course is nonsense. A better conceptualization is drawn from the classical steady state hydrodynamics, where the velocity field is determined jointly by the pressure from the sources and the suction from the sinks. Aristotle's final cause is tantamount to suction from the future; Lamarck's aphorism "the function creates the organ" is a good "slogan" for it. In spacetime, sources of entropy and negentropy respectively correspond to causality and finality (and the converse for sinks).

In this sense, d'Espagnat's[48] "idea E" that "it is impossible to influence the past" is quite questionable, as we have just seen.

Of course, as there is only world history, it is nonsense to think of rewriting it. Thus, to "kill one's grandfather in his cradle"[49] or anything of that sort[50] is out of question. But does this mean that psychokinesis (which essentially is retropsychokinesis) is nonexistent and cannot be tested? It has been tested, by Schmidt,[30] Jahn,[31] and others, through use of repetitive tests and frequency analysis. So let us examine now in what sense the frequency aspect of probability has meaning in relativistically formalized theories.

Validation of the probability concept in the classical, deterministic physics went as follows: Identity of two stochastic tests was defined up to those parameters considered negligible, if only because they were unknown. These were allowed to vary "according to the laws of chance." For example, an experimental aerodynamicist repeating a test will not worry about the lunar phase. If, when playing that sort of game, some statistical anomaly repeatedly shows up, this amounts to uncovering an overlooked "sufficient reason" (in Laplace's wording) and eventually to an important discovery, such as Planck's quantum.

Transposition of such arguments into the relativistic paradigm is easy. Up to neglected parameters, two stochastic tests can thus be said to be identical or derivable from each other by a (spacelike or timelike) translation. It is in this way that the frequency aspect of probability finds a "manifestly relativistically covariant" validation. And this is how Feynman graphs are used in particle physics. Incidentally, as "in fact" we cannot CPT reverse the environment, two CPT-associated Feynman graphs must be thought of as framed pictures.

Of course, repetitive tests and frequency analysis can be used in studies of psychokinesis, and this is what Schmidt,[30] Jahn,[31] and others have done. And this is experimental proof that (contrary to d'Espagnat's "idea E") we *can* influence the past. Moreover, it does seem that this is at the root of voluntary action; see in this respect Eccles[51] and Libet.[52]

12. MACROSCOPIC POINTER IN A SUPERPOSITION OF STATES

One often reads in textbooks that a macroscopic pointer faithfully recording some quantum magnitude is never seen in a superposition of states. This is hardly surprising as, by definition, when "seen" or "measured" accurately, a quantum magnitude is in an eigenstate! However, if one softens the meaning of "seing," then, very definitely, a pointer recording some quantum magnitude can be observed in a superposition of macroscopically distinguishable states. As an example among others (describable in S-matrix terms) there is the following procedure for measuring the linear polarization of a photon.

A birefringent crystal separates a light beam into two orthogonally polarized beams, which can then be largely separated. Thus the quantum magnitude "linear polarization of a photon" is faithfully translated into a macroscopic magnitude: appartenance to one out of two distinct beams. These are the two "positions" of our "pointer"; that they are "linearly superposed" can be verified by superposing them physically.

To "see" the pointer in one of its two positions, thus "measuring" the polarization, we must, so to speak, bring the measuring device into focus, thereby losing knowledge of the phase relation. This we can do by intercepting both beams with a photographic plate and getting one impact per detected photon.

This, according to the prequantum way of thinking, is an "objective fact," proved as such because all those looking at the plate agree upon what they see. However, our present knowledge of quantum mechanics definitely rules out that this is an objective fact; it merely is the semblance of such. It is, nevertheless, an "intersubjective fact," which raises a problem, because *a priori* one would think that subjectivity does not entail intersubjectivity!

Perhaps we will gain some insight by looking also at an other enigma. The experiments in psychokinesis show that one can "collapse the state vector" by an appropriate effort of will. Once this is accepted, it seems odd that the state vector can collapse by itself. A joint solution of this enigma and the preceding one may be an appeal to Jung's concept of a "collective unconscious." It is it, perhaps, that cuts at some level the Gordian knot of phase relations and builds up the common daydream which (inside some community), is called "reality."

It seems to me that experimental investigations of the Schmidt[30] sort should be pursued, where random events are recorded, but played back only later. It turns out that they do display statistical biasing when first looked at by a psychic.

It may be that, educated as we are by our experience at the macrolevel, we do not have the "true perception" fitting the microlevel. Shall we gain it, perhaps, by practising quantum mechanics? This is an open question.

13. CONCLUSION

Who said that the EPR correlations, an authentic offspring of the 1926 wavelike probability calculus, lack relativistic orthodoxy? The truth is that, *being Lorentz-and-Lüders invariant, they have a stronger relativistic orthodoxy than anything before them.*

While this is mathematically and operationally quite clear, it is not without raising abrupt interpretation problems, the solution of which is not to be looked for (I believe) in the line of modelism, but rather in the line of formalism—as was the case in 1905 with the relativity problem.

In a private conversation with John Bell, at the 1987 London Schrödinger Centenary Conference, I said to him that "there is only one way for getting a fully relativistic formalization of the EPR correlation." His answer was "I know what you are alluding to; but you do jump over the kinematics straight to the dynamics." I do not care for modelism, if that is what Bell had in mind, and believe that *the solution of the EPR problem entirely rests on formalism*—on a manifestly quantum-and-relativistic formalism. I believe that *the* S-*matrix scheme, as it exists, has the full answer to the* EPR *problem.*

It is strange that in 1905 Einstein had to jump over the dynamics straight to the kinematics, while (according to Bell) what I am trying to do is just the opposite. It is quite similar, however, as far as it consists of a manifestly covariant formalization devoid of any modelism.

This also is the reason why the celebrated 1964 Bell[53] theorem impresses me less than it does others. "Realism" and "separability" are to me no better superstitions than was geocentrism. What Bell's theorem does show, by *ad hoc* examples, is that some consequences of formulas (D7) and (D9) are not reproducible by formulas of the (L7) sort, *whatever the interpretation of these*. But, *formally speaking*, this is hardly surprising!

I am not in the least upset by nonseparability. Of course, "realism-and-separability" finds a straightforward expression in (L7); and, of course, (D7) implies at least nonseparability. Why then wonder, as (D7) is so well vindicated in numerous experiments?

Wavelike probability calculus, Lorentz-and-Lüders invariance, are the A and the Ω in our problem. Nonseparability, reversible conditional amplitudes, arrowless causality, are all part of the *relativistic-and-quantum* rule, that has abrogated the classical rule.

APPENDIX. ON "CURIOUS NEW PREDICTION OF QUANTUM MECHANICS" BY ALBERT, AHARONOV, AND D'AMATO (AAA).

This appendix expands footnote No. 6 referring to AAA's paper,[42] quotations from which are as follows: "Consider a quantum mechanics system [prepared] at time t_i in the state $|A=a\rangle$... and... measured at time $t_f > t_i$... in the state $|C=c\rangle$. What do these results imply about... other measurements that *might* [my italic] be carried out within the interval $t_i < t < t_f$"? Denoting as B the observable alluded to, and assuming for simplicity that the system evolves freely, AAA write down

$$P(b_j) = \frac{|\langle B=b_j | A=a\rangle| \cdot |\langle B=b_j | C=c\rangle|^2}{\sum |\langle B=b_j | A=a\rangle| \cdot |\langle B=b_j | C=c\rangle|^2}$$

for the probability that, *if* measured [their italics], the value b_j of B is found.

From the (obvious) fact that "$P(a) = P(c) = 1$, whatever $a \neq c$," AAA draw the staggering conclusion that, between times t_i and t_f, the system "must have definite values of *both* A and C, whether *or not* A and C... commute [their italics]."

This is a sophism, the root of which is easily found: That $P(a) = P(c) = 1$, even if $a \neq c$, *certainly* means that *two* different probabilities are subsumed under the same symbol. These we write, in our notation, $(B=b_j,\ C=c \mid A=a)$ and $(A=a,\ B=b_j \mid C=c)$: *two conditional probabilities, a predictive one and a retrodictive one.* The point is that the operation AAA envisage at B is a (counterfactual) "measurement-and-preparation."

We can clarify the matter by going back to the example discussed in Sec. 4: a light beam crossing in succession three birefringent crystals A, B and C. Shall we say, following AAA, that, while travelling inside B, a photon initially prepared as $|A\rangle$ and finally measured as $|C\rangle$ does have both polarizations $|A\rangle$ and $|C\rangle$? Of course not; inside B the photon is a "smoky dragon."[18] We can clinch the argument by modifying slightly our protocol: Use a simple linear polarizer at B. Then, if $|A\rangle \neq |C\rangle$, $|\langle A \mid C\rangle|^2$ is less than one, except if $|B\rangle = |A\rangle$ *or* $|B\rangle = |C\rangle$.

So, when AAA conclude that "so far as the past is concerned, the quantum formalism *requires* [their italics] that [the uncertainty relations] be violated," my comments are:

1. Why the past rather than the future? Wave retardation and arrowed causality are macroscopic emergences that should *not* be reified.
2. AAA's conundrum resurrects a quantum heresy met more than once before.
3. It is the time version of a quantum uncertainty violating heresy, the space aspect of which is suggested in EPR's[1] 1935 article.

POST SCRIPTUM

The zigzagging causality model of EPR correlations has been produced by quite a few authors in more or less equivalent forms. I quote, in chronological order of first publications, Costa de Beauregard,[54] Stapp,[55] Davidon,[56] Rayski, [57] Rietdijk,[58] Cramer,[59] Sutherland,[60] and draw attention to the footnote in a paper by Zeilinger.[61]

It need not be emphasized that there is a radical difference between the zigzagging causality EPR model and models where physical irreversibility is taken as lawlike.[29,62]

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