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CPT Invariance and Interpretation of Quantum Mechanics

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This paper is a sequel to various papers by the author devoted to the EPR correlation. The leading idea remains that the EPR correlation (either in its well-known form of nonseparability of future measurements, or in its less well-known time-reversed form of nonseparability of past preparations) displays the intrinsic time symmetry existing in almost all physical theories at the elementary level. But, as explicit Lorentz invariance has been an essential requirement in both the formalization and the conceptualization of my papers, the noninvariant concept of T *symmetry has to yield in favor of the invariant concept of* PT *symmetry, or even (as* C *symmetry is not universally valid) to that of* CPT *invariance. A distinction is then drawn between "macro" special relativity, defined by invariance under the orthochronous Lorentz group and submission to the retarded causality concept, and "micro" special relativity, defined by invariance under the full Lorentz group and including* CPT *symmetry. The* CPT *theorem clearly implies that "micro special relativity"* is *relativity theory at the quantal level. It is thus of fundamental significance not only in the search of interaction Lagrangians, etc., but also in the basic interpretation of quantum mechanics, including the understanding of the EPR correlation. While the experimental existence of the EPR correlations is manifestly incompatible with macro relativity, it is fully consistent with micro relativity. Going from a retarded concept of causality to one that is* CPT *invariant has very radical consequences, which are briefly discussed.*

1. INTRODUCTION

A preceding paper[(1)] emphasized that intrinsic time symmetry—a property shared by classical theories of dynamics, wave propagation, probability, and information, and by the quantal theories of particles and (largely)[2] of

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[2] The following discussion will show that *CPT* invariance is the covariant (and very legitimate) heir of the classical *T* symmetry.

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fields—is of critical importance in the fundamental problem of the interpretation of the quantum theory. It was stressed there that the wave collapse,[3] that is, the *stochastic event*, or *transition* of quantum mechanics shares the *time symmetry* of all elementary phenomena. An example given was the formula[4]

$$\langle x \mid a\rangle = \langle x \mid x'\rangle\langle x' \mid a\rangle \tag{1}$$

solving the Cauchy problem[(4)] for the Klein–Gordon or the spinning waves equations of Dirac, Petiau–Duffin–Kemmer, etc. In the relativistically covariant formalism of first quantization[(5)] this formula yields the expansion of the wave function $\langle x \mid a\rangle$ at any point-instant x in terms of the complete set of orthogonal Jordan–Pauli propagators $\langle x \mid x'\rangle$ with apexes x' on an arbitrary spacelike surface σ, the coefficients of the expansion being the values $\langle x' \mid a\rangle$ of the wave function on σ. Orthogonality of two Jordan–Pauli propagators with spacelike separation of their apexes x' and x'' follows from the formula

$$\langle x' \mid x''\rangle = \langle x' \mid x\rangle\langle x \mid x''\rangle \tag{2}$$

as the Jordan–Pauli propagator is zero outside the light cone.

In formulas (1) and (2) the operation $\mid x\rangle\langle x \mid$ is an invariant integral over a spacelike surface σ, in the form of the flux of the (conservative) Gordon or Dirac-style 4-current.

Formula (1) shows that the Jordan–Pauli propagator is the eigenfunction in the covariant position measurement problem,[5] formulated as, "Do we find at the pseudoinstant σ the particle crossing a given element of σ" (the corresponding probability density being the flux of the Gordon or Dirac-style current, respectively). The point is that the Jordan–Pauli propagator is nonzero inside *both* the future and the past, so that the stochastic event associated with the position measurement is a *time-symmetric* "collapse-and-anticollapse."

[3] *State vector collapse* is taken by some as a more rigorous wording. We express this concept by the shorter and more intuitive wording of *wave collapse*.

[4] We are using Dirac's notation together with his remark that an expansion $\psi^a(x) = \Sigma\, c_i^a \phi_i(x)$ can be written (summation sign omitted) $\langle a \mid x\rangle = \langle a \mid i\rangle\langle i \mid x\rangle$, where ψ and the ϕ's are interpreted as transition amplitudes. See Refs. 2 and 3.

[5] As, in the formalism of Ref. 5, the Jordan–Pauli propagator is the Fourier transform of the Fourier nucleus, the position operator associated with the Klein–Gordon equation is the four-vector x *modulo that it ends on* σ (that is, three degrees of freedom and not four; for example, the components of $\mathbf{x}$). This statement does *not* contradict the more complicated expression of the Newton–Wigner position operator, where by definition only positive frequencies are accepted, because my formalism essentially requires *both* the positive and the negative frequencies on an equal footing.[(6)]

Paradoxal as this concept may seem, it *is* the one appropriate for discussing the Einstein[(7),6] or EPR[(8),7] correlation, where (so to speak) the "dice are cast" at two (fuzzy) point-instants L and N with a spacelike separation, and are nevertheless correlated through their common past origin at C. In association with a spinning wave equation, formula (1) expresses a *position and polarization* measurement such as those performed in the Einstein[(7)] or EPR[(8)] correlation experiments.[(9)] It displays a retroactive effect, which is exactly the (paradoxical) element needed for explaining the Einstein correlation. It is *this* point that will be tested in the experiment in preparation by Aspect.[(10)]

My 1974 article[(1)] has been followed by a series of technical papers[(11)] devoted to the Einstein correlation, together with the interpretation of quantum mechanics. In these, relativistic covariance and time symmetry are systematically upheld in both the mathematical formalism and the wording. From this conjunction stems the *necessity of explicitly taking a new step.*

Time symmetry was understood in these papers[(1,11)] in the classical-sense it had in, say, the celebrated Loschmidt and Zermelo paradoxes of statistical mechanics. But time symmetry is not a Lorentz-invariant concept, so what is then really meant is "*PT* symmetry" in the sense of reversal of all four axes of spacetime.[8] But, as Lee and Yang have taught us, *PT* invariance is not the end of the story. As the physics of elementary particles is not always C invariant, we must go to *CPT* invariance, which, after general relativity and the Heisenberg uncertainty relations, ties one more connection between physics and geometry.

So, in the straight line of my previous article,[(1)] the present one aims at emphasizing that the *CPT invariance of relativistic quantum mechanics*, both in its first[(5)] and second quantized[(12)] formalization, has paramount consequences not only at the technical level of choosing interaction Lagrangians, etc., but *also at the fundamental level of understanding the interpretation of quantum mechanics.*

At this point a preliminary clarification is needed. Following Einstein[(7)] himself, some distinguished physicists have expressed more or less correlated feelings according to which the EPR[(8)] correlation implies either an open conflict[(13)] between the relativity and the quantum theories, or at least a cold

[6] In his early intuitive discussion of the paradox, Einstein incidentally referred to an apparent conflict with his special relativity theory.

[7] The analysis was there in terms of the nonrelativistic Schrödinger formalism; the sting of the paradox is still more painful in relativistic quantum mechanics.

[8] The Wigner motion reversal is *not* defined as geometrical reversal of the time axis, whereas the Racah time reversal is. This point will be discussed in Section 4. In fact, it was already *PT* symmetry that Loschmidt and Zermelo were stressing in the framework of Galileo–Newton mechanics.

war situation where a careful diplomacy in the wording can prevent a conflagration.[14] Following Stapp,[15] these theorists favor in one way or another the strategy of controlled retreat; they introduce the concept of a hidden ether,[16] conceptually providing an absolute (fluid) space and time reference frame, or else the concept[17] of particles interacting through a Dirac[18] relativistic gas and propagating in their own interior spacelike signals, moving forward with respect to the proper time.

In my opinion such ad hoc proposals are extremely artificial and doomed to failure. The history of physics has repeatedly shown that breakthroughs are gained by means of boldly consistent interpretations of an operational mathematical formalism. As examples I recall Maxwell's prediction that the squared velocity of light waves is the ratio of the electric and magnetic permeabilities of the vacuum, Einstein's reading of the group property of the Lorentz–Poincaré formulas, and Anderson's experimental confirmation of the Dirac–Weyl antiparticle concept. *Blitzkrieg* and "fleeing forward," rather than strategic retreat, gains the battles of science. Also, as will be explained in Section 3, I feel that the important experimental results[19] of Wilson *et al.* and of Bruno *et al.* are very hard to justify by means of the sort of theories just mentioned.

But then, why is it that some authors[7,13,14] feel that there is a conflict between relativity and quantum mechanics at the level of Einstein correlations, while I feel that there is none at all? The reason is that, although as elementary particle physicists they know well, and apply technically, the *CPT* invariance principle, these authors, when discussing the interpretation of quantum mechanics, fall back on Einstein's 1905 recipe for defining the special relativity theory: invariance through the orthochronous Lorentz group, and submission to the principle of retarded causality (Einstein's prohibition against telegraphing into the past). There is absolutely no doubt that special relativity understood in *this* way is incompatible with the physical reality of both the Einstein correlation[9,19] and of the time-reversed Einstein correlation.[20]

But on the other hand (and in full conformity with Eberhard's[21] statement that a treatment of the Einstein correlation which is *both relativistic and quantal* implies a rejection of the retarded causality concept), I have shown in detail[11] that *special relativity understood as invariance through the full Lorentz group, including CPT invariance, is fully consistent with the Einstein correlation.* More precisely, the physical existence of the correlation, together with assumed Lorentz invariance, *entails* invariance through the *full* Lorentz group, including *CPT* invariance. And this should certainly not come as a surprise, since the latter invariance is *the relativistic invariance of quantum field theory.*[22]

One is thus led to distinguish between *macro special relativity*, defined by invariance through the orthochronous Lorentz group and the retarded causality concept, and quantal, or *micro special relativity*, defined by invariance through the full Lorentz group and *CPT* symmetry. I find it surprising that quantal theorists do adhere to micro special relativity in their technical work, and to macro special relativity when aiming at the interpretation of quantum mechanics. My choice is the opposite: to *use micro special relativity for interpreting quantum mechanics*. And this is *Blitzkrieg*.

Another significant point in the relativistic treatment of the Einstein correlation is the antimony between two philosophies: the "advancing time" philosophy, as expressed in an often-quoted sentence of Isaac Newton, and the "four-dimensional extended spacetime" philosophy, as expressed in an often-quoted sentence of Hermann Minkowski. In the realm of quantum mechanics the Newtonian time concept (according to which, in Bergson's words, "the universe dies and is reborn at every instant t" of universal time) has reappeared in Schrödinger's famous 1926 articles, while the Minkowskian four-dimensional geometrical spirit pervades Feynman's celebrated 1949 papers. As a compromise, there is the Tomonaga–Schwinger technique of the "advancing arbitrary spacelike σ," which Dyson has proved to be mathematically equivalent to Feynman's approach.

It so happens that those authors favoring, in the interpretation of quantum mechanics, Einstein's 1905 macro relativity also favor the Tomonaga–Schwinger advancing σ philosophy—apparently because it looks more akin to the macroscopic, anthropocentric, causality concept. My *Blitzkrieg* strategy deliberately makes the opposite choice of a Feynman-style philosophy, where causality is conceived in terms of four-dimensional spacetime connections—which are *CPT* invariant. At this point one author should be quoted as having prominently recommended, in special relativity, such an approach, in an extremely elegant mathematical formalization: A. D. Fokker.[23] I am (and especially in the Einstein correlation problem) a definite follower of Fokker's "direct-action-at-a-distance philosophy" and a proponent of the time-symmetric causality concept that is implied in it. I explain in Section 3 why I deem it definitely superior to the Tomonaga–Schwinger approach for dealing with the Einstein correlation.

Section 4 discusses a technical point. It is in fact a rehabilitation of the Racah[24] time reversal, which is shown to be much more consistent with the *geometrical*, static, concept of time reversal than is the Wigner[25] motion reversal. While there certainly is an affinity between the Tomonaga–Schwinger advancing σ philosophy and Wigner's concept of motion reversal, it will be shown that, on the other hand, there is a definite affinity between Feynman's spacetime-extended-interactions philosophy and Racah's concept of time reversal.

Summarizing, the aim of the present article, following previous ones,[1,11] is to promote, as the appropriate paradigm of relativistic quantum mechanics (and, inside of it, of the Einstein correlation), the Lorentz- and *CPT*-invariant framework of "micro relativity", expressed in the Minkowski and Feynman style of an extended spacetime geometry. Philosophically speaking, this entails (as clearly recognized by Eberhard[(21)]) the replacement of the classical retarded causality concept by a *CPT-invariant microcausality concept*. From this *necessarily* follow some dramatic consequences, which are briefly discussed in Section 5.

2. LORENTZ PLUS *CPT* INVARIANCE IN THE PREPARATION AND MEASUREMENT PROBLEM

1. As previously said, the T operation is here understood as geometrical reversal of the time axis, just as the P operation is understood as geometrical reversal of the three space axes. Thus, our T operation (which we will term the Racah[(24)] time reversal) is different from the Wigner[(25)] motion reversal $\mathscr{T}$ operation generally used in quantum physics, whereas $P \equiv \mathscr{P}$. The PT operation reverses all four components of four-vectors, including of course energy—momentum, whereas the $\mathscr{C}\mathscr{C}$ operation reverses the momenta and not the energies. The PT operation leaves unchanged the six-component angular momenta, and thus reverses helicities.

The PT operation just defined exchanges particles and antiparticles as defined *à la* Stuckelberg–Feynman. Therefore, in this scheme, we set by definition $C^{-1} \equiv PT$, whence $CPT = 1$ (which is a reinterpretation of the $\mathscr{C}\mathscr{P}\mathscr{T}$ invariance theorem[(22)]). Obviously, C or PT noninvariance entails chirality noninvariance. Considered as a passive transformation the PT symmetry will reverse all the Feynman arrows, so that, in order to restore the original situation, we must reverse the signposts, that is, exchange particles and antiparticles. So, CPT invariance is truly built into the Feynman scheme (and the C, P, T philosophy is more in harmony with it than is the $\mathscr{C}$, $\mathscr{P}$, $\mathscr{T}$ philosophy).

2. Now, considered as an active transformation, a CPT symmetry performed on a Feynman diagram (Fig. 1) will exchange[9] the preparations L_1, M_1, N_1,... and the measurements L_2, M_2, N_2,..., so that a major consequence of my basic assumption is *intrinsic symmetry between the*

[9] It should be noted that the Feynman propagator $D_{F(-)} \equiv \bar{D} - \frac{1}{2}(D_+ + D_-)$ is PT invariant, as is the anti-Feynman propagator $D_{F(+)} \equiv \bar{D} + \frac{1}{2}(D_+ + D_-)$ obtained by sidestepping the two poles the other way around. As is well known, use of the Feynman propagator ensures automatically an exponential decay if used in prediction (but, symmetrically, an exponential buildup if used in retrodiction). The opposite would follow from use of the anti-Feynman propagator. See Ref. 35, p. 408.

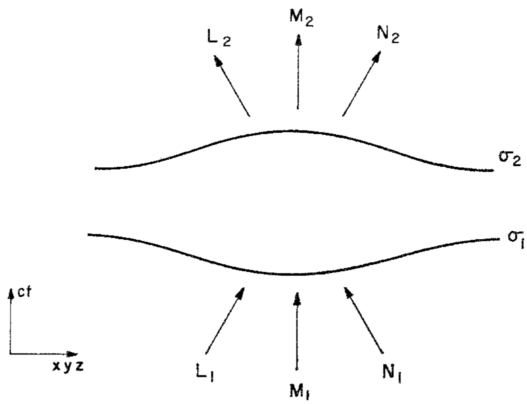

Fig. 1. The S-matrix formalism (interaction picture). CPT invariance entails reciprocity between preparations L_1, M_1, N_1 and measurements L_2, M_2, N_2. The CPT-invariant collapse-and-anticollapse concept consists in one element $\langle \Phi_i \mid \Psi_j \rangle$ of the transition matrix being selected.

preparation and measurement concepts—a feeling certainly not shared by d'Espagnat[(13)]—but does a scientific revolution[(26),10] go on without "sound and fury"?

3. Thus CPT invariance (just as $\mathscr{CPT}$ invariance) entails a "detailed balance theorem" of the form $(A + B + \cdots \rightarrow P + Q + \cdots) \sim (\bar{P} + \bar{Q} + \cdots \rightarrow \bar{A} + \bar{B} + \cdots)$, but something more can be said. If C invariance does not hold, $C(PT)$ invariance does, and *this* is exactly the four-dimensional analog of the $\mathscr{CP}$ invariance concept[(36)] which has large, but not universal validity. The feeling of uneasiness created by the $\mathscr{CP}$ violation in K-meson decay may thus be alleviated by going to the symmetries of four-dimensional geometry.

4. Again considered as an active transformation, a CPT symmetry will change the nonseparability of future measurements upon subsystems that have interacted[(9,19)] into nonseparability of past preparations that will interact.[(20)] I have used[(11)] this argument as a priori supporting conservation of the correlation formula between linear polarization states at very large spatial distances,[(19)] and also in Aspect's[(10)] experiment, where the polarizers are turned while the photons are flying, because common sense believes the time-reversed statements to be obvious. The latter could of course be tested[(11)] in anticascade experiments, which have become routine since the advent of

[10] The essence of Kuhn's philosophy is already found in Duhem.[(27)]

the dye laser.[11] So, if one does not question retarded causality in the time-reversed, anticascade experiments, the *CPT*-invariance principle renders useless the Wilson *et al.*, Bruno *et al.*, and Aspect experiments. But, on the other hand, as Born's probabilistic interpretation of quantum mechanics in the form of a "wavelike probability calculus" forbids[(11)] that the correlated measurements in an *EPR* experiment (or the correlated preparations in a time-reversed *EPR* experiment) do confer *properties belonging* to the subsystems, the retarded causality concept may then seem less obvious than it was with the classical calculus of probabilities. Then the *CPT*-invariance principle may be used to link experimental results of the direct and the reversed *EPR* correlation experiments.

5. My *CPT*-invariance basic philosophy certainly requires that I define and use a time-symmetric concept of the wave collapse. This, as recalled in the Introduction, I have largely done in my series of papers.[(11)] In the context of the *S*-matrix formalism the following *CPT*-invariant concept of the wave collapse holds: given the Schwinger–Feynman transition amplitude $\langle \Phi \mid \Psi \rangle$ between a specified set of preparations $\mid \Phi \rangle$ and a specified set of measurements $\mid \Psi \rangle$, the single stochastic event, or *collapse*, consists in that *one element* $\langle \Phi_i \mid \Psi_j \rangle$ *of the transition amplitude matrix is actualized.*

Then one can either consider a predictive problem, by collecting the various outcomes of a given preparation, or a "blind"[(29)] retrodictive problem, by collecting the possible preparations of a given measurement result. For computing the corresponding sets of probabilities, it is convenient to project respectively $\mid \Phi \rangle$ upon $\mid \Psi \rangle$, which is termed *collapsing* the wave function, or to project $\mid \Psi \rangle$ upon $\mid \Phi \rangle$, which I call *anticollapsing* the wave function. These are two asymmetric (but symmetric to each other) ways of thinking of, and computing, the Hermitian scalar product—which is intrinsically symmetric in $\mid \Phi \rangle$ and $\mid \Psi \rangle$.

Clearly, the predictive procedure uses retarded waves, while the retrodictive procedure uses advanced waves, a fact recognized by Fock,[(30)] Watanabe,[(29)] and others.[(31)] Born's "wavelike probability calculus" essentially links together *lawlike symmetry* and *factlike asymmetry* of, on the one hand, *predictive and retrodictive probabilities* and of, on the other hand, *retarded and advanced waves.*

6. A very important point should now be stressed, which will be expanded in Section 3. The (wavelike) probability calculus used in quantum mechanics essentially is a *conditional probability* calculus: it holds "if" such preparation and "if" such measurement, *as specified in the formula,* is performed.

[11] See Ref. 28 for an anticascade experiment with polarizers.

Therefore, the S-matrix transition amplitude $\langle \Phi \mid \Psi \rangle$ (Fig. 1) essentially holds *if* each and every of the ingoing preparations L_1, M_1, N_1,..., and each and every of the outgoing measurements L_2, M_2, N_2,..., *as stated in the formula*, are performed.

It is thus clear that the probability concept inherent in quantum mechanics (here, in relativistic quantum mechanics) is *neither objective nor subjective, because it is both.* Probability (whence, also, *information*) thus appears as *the hinge around which mind and matter are interacting*—a point to be further expanded in Section 5, in the context of *CPT*-invariance.

So, finally, the *paradoxical fact* is that the so-called *local* preparations L_1, M_1, N_1 ,... and measurements L_2, M_2, N_2,... are *nonseparable.* I have argued[11] that *the only conceivable connection between them is through the Feynman zigzags* (Fig. 1) *via the interaction region C*, as implied by the very mathematics, and also required by the physics—as these zigzags are *the only occupied channels.*

Thus, the Einstein[7] or EPR[8] *paradox is born from the union of two earlier paradoxes: intrinsic time symmetry* in the Loschmidt and Zermelo fashion, and *wavelike probability calculus à la* Born. The Einstein or EPR correlation is tied via the Feynman zigzags, either as a nonseparability of future measurements via their common past preparation[9,19] (Einstein correlation proper), or as a nonseparability of past preparations via their common future measurement[20] (time-reversed Einstein correlation).

CPT invariance and wavelike calculus of probabilities are built into the Feynman treatment of the S-matrix. They show up together as the paradoxical Einstein correlation—the wizard of which is the Feynman zigzag.

3. DISCARDING A FREQUENT MISCONCEPTION

1. As an example consider a pair of photons a and b moving oppositely along an axis x in the laboratory frame, prepared in one of the two spin-zero states[32]

$$\sqrt{2}\,\Psi = L_a L_b \pm R_a R_b = \begin{cases} Y_a Y_b + Z_a Z_b \\ i[Y_a Z_b - Z_a Y_b] \end{cases} \tag{3}$$

and suppose that a (circular or linear) polarization measurement is performed on photon a alone. It is true that it does collapse the a substate into either L_a or R_a, or Y_a or Z_a. But it would be utterly wrong to then conclude, by carelessly reading formulas (3), that it does also collapse *physically* the b substate into, respectively, L_b or R_b, or Y_b or Z_b, or Z_b or Y_b.

This is easily shown by the following *reductio ad absurdum.* We can measure simultaneously in the laboratory frame the *circular polarization* on photon a and the *linear polarization* on photon b, the corresponding transition amplitude being

$$2\Psi = L_a Y_b + iL_a Z_b \pm R_a Y_b \mp iR_a Z_b \tag{4}$$

The question is of course: *which* of the two measurements collapses the *other* substate?

Moreover, the two measurements need not even be simulatneous, because *the correlation formula is symmetric in a and b*, and thus *invariant with respect to the time ordering of the measurements.*

In the case of photons, the measurements performed upon a and b always define a spacelike vector LN, so that the time ordering $t_a - t_b$ is *relative* in an (x, t) Lorentz transformation. And, as such a Lorentz transformation conserves the (circular or linear) polarization states, it is completely meaningless to conceive of a wave collapse occurring "first" at L (or N) and then affecting "instantly" the other photon b (or a).

One further step should be taken. Not only the relative distances $x_L - x_C$ and $x_N - x_C$ between the detectors L and N and the source C, but also (Fig. 2) the relative velocities along x, $v_L - v_C$ and $v_N - v_C$, are arbitrary, the polarization states being invariant with respect to v_C, v_L, v_N. Therefore, *it is absolutely excluded that a preferred reference frame exists for formalizing and understanding the Einstein correlations* (as some authors have suggested).

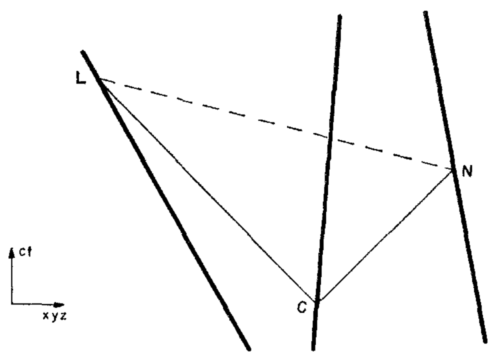

Fig. 2. The source C (cascading atoms) and the detecting devices L and N can have arbitrary velocities inside an (x, ct) plane, and the time ordering of the detecting events is relative in an (x, ct) Lorentz transformation. Therefore it is excluded that a preferred reference frame exists for describing the Einstein correlation.

So, finally, what is the answer to the question raised by the reductio ad absurdum argument? It is (as previously stated): *a word "if" is attached to each and every symbol L, R, Y, or Z present in the formulas* (1) *and* (2). It is under *this* assumption that a collapse of photon a into L_a, R_a, Y_a, or Z_a, collapses the photon b into, respectively, L_b, R_b, Y_b (or Z_b), or Z_b (or Y_b): *if* the *strictly correlated* measurement is performed on photon b.

And *what* if no measurement at all is performed on photon b? Well, as a measurement performed on photon a alone is *definitely not* a proper measurement upon the a and b system, then *nothing at all can be said of b.*

2. In the S-matrix context, when two measurements L and N are said to be performed upon subsystems a and b, the verb "to be" is understood in the atemporal sense appropriate to Minkowski's four-dimensional geometry. If, instead, we choose everyday language, the appropriate wording becomes: *If* (say) a circular polarization measurement performed upon a yields (or has yielded, or will yield) (say) the L_a state, then, *if* a circular polarization measurement is (or has been, or will be) performed upon b, it yields (or has yielded, or will yield) the L_b state.

3. Things being so, the superiority of the Feynman philosophy over the Tomanaga–Schwinger philosophy consists in the following:

In the nonrelativistic Schrödinger formalism, which the covariant Tomonaga–Schwinger approach mimics to a certain extent, one of the two collapses, say L, occurs first, and is thought of as collapsing the overall $|\Phi\rangle$ into, say, $|\Psi\rangle$. Then, the "second" measurement N collapses $|\Psi\rangle$. It finally turns out that the correlation formula is symmetric in L and N. The difference between the Schrödinger and the Tomonaga–Schwinger treatments is that, in the first one, the time ordering of the collapses is absolute, whereas in the latter it is relative to the σ family, and therefore is reversible (if the LN vector is spacelike).

It is thus clear that the asymmetry in the reasoning and in the computation is spurious, and just as irrelevant as the ordering of credit and debit entries in a recording of accounts, where the order of the entries does not affect the overall balance.

The point is that, thanks to its use of propagators in the spacetime picture,[(33)] or of the eigenfunctions of the four-frequency picture,[(11)] *the Feynman method directly displays the L and N symmetry of the correlation formula.*

Therefore, notwithstanding its remoteness from common sense (or, should we rather say, *because* of it), the Fokker[(23)] and Feynman philosophy is the most appropriate one to our problem.[12] And this, of course, brings us

[12] Suppose some archaeologists discover that similar cultures have developed along two converging rivers running through barren country. Will they assume that there has been

back to Eberhard's[21] statement that a radical change in the causality concept is required by the Einstein correlations in relativistic quantum mechanics.

4. RACAH VERSUS WIGNER TIME REVERSAL

While the well-known Wigner[25] motion reversal operation $\mathscr{T}$ is obviously quite consonant with the Schrödinger advancing time, and the Tomonaga–Schwinger advancing σ, philosophy, the Racah[24] time reversal operation T is generally discarded with little comment as being nonphysical. It can be consistently used, however, as recognized by Watanabe[34] and by Jauch and Rohrlich.[35] We intend to show here that (as defined in the framework of the Dirac electron theory) the Racah time reversal T *exactly* is the geometrical reversal of the time axis which is appropriate in the four dimensional spacetime geometry, and is thus *naturally akin to the Feynman zigzag philosophy.*

Consider, in units such that $c = 1$ and $\hbar = 1$ ($i, j, k, l = 1, 2, 3, 4$; $x^4 = it$), the Dirac equation,

$$\{\gamma^i(i\partial_i - eA_i) + m\}\psi = 0 \tag{5}$$

and define $\gamma^{ij} \cdots \equiv \gamma^i\gamma^j \cdots$ if all indexes are different. Obviously, the operations ($\gamma^5 \equiv -\gamma^{1234}$)

$$\psi' = \gamma^i\psi, \qquad \psi'' = i\gamma^{jkl}\,\psi, \qquad \psi''' = -\,\gamma^{1234}\,\psi = \gamma^5\psi \tag{6}$$

respectively reverse axes (j, k, l), (i), and (i, 2, 3, 4). Thus, in particular,

$$P\psi = \gamma^4\psi \text{ (well known)}, \qquad T\psi = \gamma^{123}\,\psi \text{ (Racah)}, \qquad PT\psi = \gamma^5\psi \tag{7}$$

Under the PT operation, e and m are (by definition) invariant; $i\partial_i$, A_i, and the four-currents $i\bar{\psi}[\partial_i]\psi$ and $i\bar{\psi}\gamma_i\psi$ behave as true vectors—they change sign.

The electric charge Q, defined by

$$24Q = \epsilon_{ijkl} \iiint j^i\, d_1x^j\, d_2x^k\, d_3x^l \tag{8}$$

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some direct interaction between any site on one river and any site on the other. Or rather, that the influence has travelled up and down, via navigation on the rivers.

where ϵ_{ijkl} denotes the Levi-Civita object, and d_1x^j, d_2x^k, d_3x^l are three four-vectors collinear neither to each other nor to the four-current j^i, obviously behaves as a true scalar,[13] which is consistent with the invariance of e.

It is obvious in (5) that the change in sign of all four components of the vector $i\partial_i - eA_i$ in a PT symmetry is equivalent to changing the sign of the mass term m. Therefore, by requiring that

$$CPT \equiv 1 \tag{9}$$

we can define the C operation as changing the sign of the mass m, which (as e is invariant by definition) changes the sign of e/m.

As the six-component angular momentum $x^ip^j - x^jp^i$ is invariant by the PT symmetry, the helicity is changed. Therefore, C noninvariance essentially means helicity noninvariance.

On the whole, this CPT system of concepts is geometrically very symmetric, and quite consonant with the Feynman zigzag philosophy. There is no doubt that it can be used consistently. One potential advantage in it is that *all three operations* C, P, T *are unitary*, with eigenvalues ± 1; for example, the Jordan–Pauli propagator has parities $P = +1$, $T = -1$, $PT \equiv C = -1$.

Of course, going from the familiar $\mathscr{C}$, $\mathscr{P}$, $\mathscr{T}$ system of concepts to the more geometric C, P, T system entails drastic changes in thinking habits (but so does the Feynman zigzag scheme, where the three-momentum $\mathbf{p}$ of antiparticles is opposite to their three-velocity $\mathbf{v}$). For one thing, the $\mathscr{C}\mathscr{P}$ invariance of weak interactions goes into a PT invariance. As an example, consider the Weyl neutrsno and antineutrino pair $W = \boldsymbol{\sigma} \cdot \mathbf{p}$. The antineutrino will be interpreted as a negative-energy neutrino $-W = |\mathbf{p}|$ rather than the mirror image $W = -|\mathbf{p}|$ of the neutrino $W = |\mathbf{p}|$. Neutrino and antineutrino will thus have the same (left-handed) helicity. The C symmetry then consists in going to the interpretation where both the neutrino and antineutrino are right-handed, and have (respectively) a negative and a positive energy. CPT invariance is obvious.

Thus, the familiar energy asymmetry of the usual scheme (only positive energies) has been exchanged for a helicity asymmetry.

The *inevitable* appearance of negative energies in this scheme renders the familiar expression of conservation laws by means of spacelike integrals σ less convenient than in the usual scheme. But, on the other hand, the C, P, T scheme (as already said) is quite consonant with the Feynman zigzag scheme.

[13] Jauch and Rohrlich[(35)] make the surprising statement that it does *not*; this is because they do not reverse (as they should) the sign of the three-volume element.

5. THE MOST OMINOUS CONSEQUENCE OF *CPT* INVARIANCE: RECIPROCITY OF THE CONVERSION NEGENTROPY — INFORMATION

In his famous book *Symmetries and Reflections*, Wigner(37) expresses a very bold—but very logical—assumption. He argues, from both the general principle that to every "action" there corresponds a "reaction," and from the specific interpretation scheme of quantum mechanics, that *there should exist a reaction of the observer upon the observed.*[14] Wigner goes even so far as adding: "Every phenomenon is unexpected and most unlikely until it has been discovered—and some of them remain unreasonable for a long time after they have been discovered." He says also that he knows of no philosopher having already uttered such a statement. There is at least one, however (and this may come as a surprise): Descartes.(38)

The general principle of CPT invariance upheld in this paper obviously entails the conclusion already drawn by Wigner. If, following the Copenhagen–Göttingen school, the stochastic event of *wave collapse* is attributed to an act of consciousness of the observer, then, via the principle of *CPT* invariance, it is (as already said) *a collapse-and-anticollapse*, so that the act of cognizance (the by-product of which is the emission of a retarded wave) is coupled to an act of will (the by-product of which is the absorption of an advanced wave). As an example of this intrinsically time-symmetric phenomenon we have discussed(11) the covariant position measurement process. As previously said, asymmetry shows up *only* at the macro level, and it is, in Mehlberg's(39) words, *factlike* and *not lawlike.*

What we are saying is none else than a very familiar statement in information theory. The information concept has two faces: gain in knowledge and organizing power, which show up, respectively, in (say) the reception and the emission of a message. And this was already khown to Aristotle (and, more explicitly, to Thomas Aquinas). To say that information as knowledge is a trivial concept, and information as organization a somewhat esoteric concept, is none else than a statement of the Second Law—which is factlike. It is, I believe, the deepest of all expressions of the Second Law.

But now, very much as there is a lawlike symmetry and a factlike asymmetry between particles and antiparticles, *and* that, knowing this, it is not impossible to unveil the hidden, negative, face of energies, so it must be possible to unveil also the hidden, advanced, face of the information waves

[14] In almost all textbooks on quantum mechanics it is stated that there is a reaction of the measuring apparatus upon the observed system. It is *very strange* that a *necessary* consequence of this statement is not drawn, namely, the reaction of *the observer* upon the so-called observed system—because, *where* is the severance between the observer and the measuring apparatus.

of quantum mechanics. All the more so that there is a partial binding between these two lawlike symmetries and factlike asymmetries. It is well known that, by definition, the Feynman propagator links positive energies with the retardation, and negative energies with the advance, concept. Also, the Jordan–Pauli propagator has the two expressions

$$D \equiv D_{+} - D_{-} = D_{\text{ret}} + D_{\text{adv}}$$

It goes without saying that accepting the appearance of advanced waves at the macro level means acceptance of the phenomena termed *precognition* and *psychokinesis* in parapsychology—two phenomena not distinguishable from each other at this level of the discussion. Other physicists have made, in a slightly different context, an essentially identical statement.[(40)]

Schmidt[(41)] has very carefully discussed the phenomenology of a small contribution of advanced waves against a strong background of retarded waves, and has shown that it is no more incompatible with the routine working of macrophysics than is a small contribution of antiparticles against a strong background of particles. Schmidt's contribution is significant, because it disposes of sweeping statements of the kind, "As one cannot kill one's grandfather in his cradle, the (macroscopic) advanced waves concept is a priori ridiculous." Was it not Lavoisier who stated that, "As there are no stones inside the sky, no stones can fall from the sky"?

Schmidt had good reasons in writing the quoted paper. He has published, in respected journals, the positive results of experiments in psychokinesis, and not only of "real-time" ones,[(42)] but also of retroactive ones.[(43)] The latter, of course, are *extremely* paradoxical. What I intend to show now is that *they are necessarily implied for consistency of the Copenhagen–Göttingen interpretation of quantum mechanics.*

If it is true that it is the act of observation that collapses the wave function, *what* if the result of a measurement is recorded automatically and read only later? Of course it must be read at some time, otherwise nothing can be said.

Schmidt's[(43)] retropsychokinetic experiments provide an answer to this question, and I cannot imagine any other one. Fantastic as it looks, this answer is not contrary to facts,[(41)] and even, says Schmidt,[(43)] it *is* fact.[15]

Of course, it would be quite significant to couple an EPR correlation experiment with a psychokinetic experiment, and thus see if psychokinesis performed on one beam would affect the other one. An attempt has been made in this direction, with a negative result,[(44)] but, as an essential ingredient was missing—psychokinesis on one beam—the experiment in itself was nonsignificant.

[15] "Your theory is crazy, but is not crazy enough to be true" (N. Bohr). "For any speculation which does not at first glance look crazy, there is no hope" (F. J. Dyson).

It has been repeatedly stated[13] that the Einstein spacelike correlation cannot be used for telegraphing outside the light cone. This is undoubtedly true if one tries to use it in connection with some gadget—because of the (factlike) Second Law. But if we can overcome the Second Law by making use of the reciprocity of the conversion *negentropy* ⇌ *information* through psychokinesis, telegraphing outside the light cone via Feynman zigzags becomes possible.

6. PHENOMENOLOGY OF *CPT* INVARIANCE

Duhem,[27] and quite a few others after him, have convincingly shown that there is no such thing as a crucial experiment. Acceptance of a new paradigm therefore builds up through an accumulation of observed facts in conformity with it.

As previously said,[11] one main aspect of the paradigm I am proposing is that the link of the distant Einstein correlation is a Feynman zigzag, with the connection either in the past or in the future. I review here some of the facts which are explained in a quite straightforward way by this hypothesis, but some of which do not seem to be so easily justifiable in other schemes.

1. Nonseparability of two distant stochastic measurements[9,19] or of two distant preparations [20] physically connected through their common past or future, respectively.

2. Intrinsic symmetry between these two concepts, as experimentally verifiable.

3. Theoretically predicted, and experimentally verified,[19] invariance of the correlation formula through arbitrary displacements of the measurement events along the respective beams. This really amounts to a geographical exploration of the streams forming the Feynman zigzag that channels the correlation (see footnote 12).

4. Aspect's[10] experiment (if it turns out as supporting quantum mechanics).

5. The Einstein correlation plus psychokinesis experiment, as defined at the end of Section 5 (if it yields a positive answer).

6. Schmidt's[43] retropsychokinesis experiments.

7. CONCLUSION

My formalization and interpretation of the 1927 Einstein[7] and 1935 EPR[8] correlation strictly adheres to the mathematics of relativistic quantum mechanics, either in its second quantized Tomonaga–Schwinger–Feynman–Dyson expression, or in the first quantized expression I have proposed.[5] It consists in a straightforward reading of the (very operational) mathematics: no more, but no less, than "the scriptures." In this, I believe, I am carefully listening to some illustrious teaching: Copernicus and Einstein (not to speak of others) have unveiled the sense of the scriptures by wording a discourse exactly fitting an operational mathematical recipe: heliocentric kinematics, or Lorentz–Poincaré kinematics. It then turned out that a large collection of (sometimes paradoxical) phenomena, other than those already taken care of, but also implicit in the formalism, were true.

My guess is that the various consequences of Lorentz plus *CPT* invariance (as tied in with Born's wavelike principle of adding partial amplitudes), pursued in the most systematic and uncompromising way, will open new vistas in the problem of the interaction between mind and matter. These, implied in the very concept of probability, are enunciated with much more acuity through the use of Born's principle, in the quantal measurement problem.

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REFERENCES

1. O. Costa de Beauregard, *Found. Phys.* **6**, 539 (1976).
2. P. A. M. Dirac, *The Principles of Quantum Mechanics* (Oxford Clarendon Press, 1948), p. 79.
3. A. Landé, *New Foundations of Quantum Mechanics* (Cambridge University Press, 1965), p. 83.
4. J. Schwinger, *Phys. Rev.* **74**, 1439 (1948); see p. 1451.
5. O. Costa de Beauregard, *Précis de mécanique quantique relativiste* (Dunod, 1967); see also *Synthese* **35**, 129 (1977), p. 143 [reprinted in *Hans Reichenbach, Logical Empiricist*, W. C. Salmon, ed. (D. Reidel, 1979), pp. 341–366].
6. R. F. O'Connell, private communication.
7. A. Einstein, in *Rapports et Discussions du 5e Conseil Solvay* (Gauthier Villars, 1928), pp. 253–256.
8. A. Einstein, B. Podolsky, and N. Rosen, *Phys. Rev.* **47**, 777 (1935).
9. S. J. Freedman and J. F. Clauser, *Phys. Rev. Lett.* **28**, 938 (1972); J. F. Clauser, *Phys. Rev. Lett.* **36**, 1223 (1976); E. S. Fry and R. C. Thompson, *Phys. Rev. Lett.* **37**, 465 (1976).
10. A. Aspect, *Phys. Lett.* **54A**, 117 (1975); *Phys. Rev. D* **14**, 1944 (1976).
11. O. Costa de Beauregard, *Nuovo Cim.* **42B**, 41 (1977); **51B**, 267 (1979); *Lett. Nuovo Cim.* **19**, 113 (1977); **25**, 91 (1979); *Phys. Lett.* **60A**, **93** (1977); **67A**, 171 (1978).

12. S. I. Tomonaga, *Prog. Theor. Phys.* **1**, 27 (1946); J. Schwinger, *Phys. Rev.* **74**, 1439 (1948); F. J. Dyson, *Phys. Rev.* **75**, 486 (1949); R. P. Feynman, *Phys. Rev.* **76**, 749, 769(1949).
13. B. D'Espagnat, *Conceptual Foundations of Quantum Mechanics*, 2nd ed. (Benjamin, 1976), pp. 90, 119, 238, 265, 281.
14. J. F. Clauser and A. Shimony, *Rep. Prog. Phys.* **41**, 1881 (1978); see p. 1920.
15. H. P. Stapp, *Found. Phys.* **7**, 313 (1977).
16. B. D'Espagnat and J. S. Bell, private communications.
17. N. Cufaro Petroni and J. P. Vigier, *Lett. Nuovo Cim.* **25**, 151 (1979).
18. P. A. M. Dirac, *Nature* **168**, 906 (1951).
19. A. R. Wilson, J. Lowe, and D. K. Butt, *J. Phys. G* **2**, 613 (1976); M. Bruno, M. d'Agostino, and C. Maroni, *Nuovo Cim.* **40B**, 143 (1977).
20. R. L. Pflegor and L. Mandel, *Phys. Rev.* **159**, 1084 (1967); *J. Opt. Soc. Am.* **58**, 946 (1968).
21. P. Eberhard, *Nuovo Cim.* **46B**, 392 (1978).
22. G. Lüders, *K. Dansk Videns. Selsk.* **28**, 5 (1954); *Ann. Phys.* **2**, 1 (1957); W. Pauli, in *Niels Bohr and the Development of Physics*, W. Pauli, L. Rosenfeld, and V. Weisskopf, eds. (Pergamon, 1955), p. 30.
23. A. D. Fokker, *Time and Space, Weight and Inertia* (Pergamon, 1965).
24. G. Racah, *Nuovo Cim.* **14**, 322 (1937).
25. E. Wigner, *Gott. Nachr.* **31**, 546 (1932).
26. T. S. Kuhn, *The Structure of Scientific Revolutions*, (University of Chicago Press, 1962; 2nd ed, 1970).
27. P. Duhem, *The Aim and Structure of Physical Theory* (translated after the 1913 French edition by P. P. Wiener; Princeton Univ. Press), Part II, Chapters 4 and 6.
28. P. F. Liao and G. C. Bjorklund, *Phys. Rev. Lett.* **36**, 584 (1976).
29. S. Watanabe, *Rev. Mod. Phys.* **27**, 179 (1955).
30. V. Fock, *Dokl. Akad. Nauk SSSR* **60**, 1157 (1948).
31. O. Costa de Beauregard, *Cah. de Phys.* **2**, 317 (1958); Y. Aharonov, P. G. Bergmann, and Y. Lebowitz, *Phys. Rev.* **134B**, 1410 (1964); F. J. Belinfante, *Measurements and Time Reversal in Objective Quantum Theory* (Pergamon, 1975); P. C. W. Davies, *The Physics of Time Asymmetry* (Surrey Univ. Press, 1974).
32. O. Costa de Beauregard, *Lett. Nuovo Cim.* **26**, 135 (1979).
33. R. Payen and J. M. Vigoureux, *Lett. Nuovo Cim.* **20**, 263 (1977).
34. S. Watanabe, *Phys. Rev.* **84**, 1008 (1951).
35. J. M. Jauch and F. Rohrlich, *The Theory of Photons and Electrons* (Addison-Wesley, 1955); see pp. 88–96.
36. T. D. Lee and C. N. Yang, *Phys. Rev.* **105**, 1671 (1957); L. D. Landau, *Nucl. Phys.* **3**, 127 (1957); A. Salam, *Nuovo Cim.* **5**, 299 (1957).
37. E. Wigner, *Symmetries and Reflections* (MIT Press, 1967), pp. 171–184.
38. R. Descartes, *Lettres* (Adam and Tannery, eds.), Vol. I, p. 222 (letter 525); Vol. III, p. 663 (letter 302).
39. H. Mehlberg, in *Current Issues in the Philosophy of Science*, H. Feighl and G. Maxwell, eds. (Holt, Rinehart, Winston, 1961), p. 105.
40. E. H. Walker, in *Quantum Physics and Parapsychology*, L. Oteri ed. (Parapsychology Foundation, 1975), p. 1; R. D. Mattuck and E. H. Walker, in *The Iceland Papers*, A. Puharitch ed. (Essentia Research Associates, Amherst, 1979), p. 111.
41. H. Schmidt, *Found. Phys.* **8**, 464 (1978).
42. H. Schmidt, *Bull. Am. Phys. Soc.* **24**, 38 (1978).
43. H. Schmidt, in *Proc. Intern. Conf. Cybernetics and Society* (IEEE 1977), p. 535.
44. J. Hall, C. Kim, McElroy, and A. Shimony, *Found. Phys.* **7**, 759 (1977).