EINSTEIN–PODOLSKY–ROSEN CORRELATIONS: THEIR LORENTZ- AND CPT INVARIANCE

O. Costa De Beauregard
Institut Henri Poincaré
France

This paper is organized as follows: I - Einstein's remarks at the Fifth Solvay Council. II - Macro- and micro-relativity. III - CPT-invariance as generalized Loschmidt T-invariance. IV - A typical EPR correlation: correlated linear polarizations of photons. V - Lorentz-and-CPT invariance of the EPR transition amplitude for photon pairs. VI - Other implications of the S-matrix scheme. VII - Additional informations. VIII - Concluding remarks.

I - EINSTEIN'S REMARKS AT THE FIFTH SOLVAY COUNCIL

What came to be known as the Einstein-Podolsky-Rosen (E.P.R.)[1] paradox[2] is really anticipated in Einstein's[3] penetrating remarks at the Fifth Solvay Council. There, over the very cradle of the "new quantum mechanics" surrounded by its "founding fathers", he discussed an example of a distant correlation between two measurements at L and N issuing from a common preparation at C, pointing clearly to the two essential ingredients of the enigma.

First, according to Born's 1926 statistical interpretation of the wave mechanics[4], where partial amplitudes rather than probabilities are added, and independant amplitudes rather than probabilities are multiplied, it is definitely not at C, where "they are shaken together in the cup", but rather at L and N, "where they stop rolling on the table", that, so to speak, "the dice are cast"[5]. Nevertheless they are correlated - which of course is paradoxical!

Second, at first sight such a correlation seems to contradict a fundamental assumption of the relativity theory, where faster than light telegraphing is forbidden.

In 1953 I argued[6] that there exists a very obvious, at first sight shocking, but at second sight respectable, way out of this dilemma. While the spacelike vector LN, being physically empty, certainly cannot carry any "telegram", the zigzag LCN, consisting of two timelike vectors, is physically occupied[7]; moreover, as shown by the very mathematics, it does carry the correlation between the measurements at L and N. Therefore, if we take notice that all known elementary phenomena in dynamics, in wave theory, and in the probability calculus per se[8], are time symmetric[9], we must say that the causality concept has to be arrowless at the elementary level. And so, although they are "cast" at L and N, the "dice", as "measured" at L and N, may very well be correlated via their past "preparation" at C.

Such a proposal is none else than a quantal and relativistic extension[10] of Loschmidt's 1876 reversibility statement, which truly lies deeper than in statistical mechanics: in the probability calculus per se. It still holds in the Born 1926 wavelike probability calculus, and in the relativistic expressions of quantum mechanics.

II - MACRO- AND MICRORELATIVITY

Special relativity, as conceived by Lorentz, Poincaré, and finally Einstein, states that the physical laws are invariant under the orthochronous Lorentz group. Thus defined it is a macroscopic theory, and is consistent with the irreversibility statements of wave retardation and of increasing probability: as Einstein wrote "one cannot telegraph into the past". This is most certainly a macroscopic prohibition, and is not consonant with Loschmidt's reversibility statement (1876).

As for this Loschmidt motion reversal statement, it certainly needs a rewording rendering it (orthochronously) Lorentz invariant. As expressed in terms of the Poincaré-Minkowski spacetime, motion reversal is covariantly formalized as geometrical reversal $\Pi\theta$ of all four spacetime axes. It turns out, however, that our intuitive feelings concerning motion reversal are better rendered by expressing the $\Pi\theta = 1$ invariance as the CPT = 1 invariance[11,12], where C means particle-antiparticle exchange and PT "covariant motion reversal" - as discussed in the following section.

As is well known, in 1946-49 Tomonaga, Schwinger, Feynman and Dyson produced the relativistically covariant formalization of quantum field theory. As a natural sequel, Schwinger, Lüders and Pauli showed, in 1952-56, that this theory has a stronger invariance than the 1905 orthochronous Lorentz invariance: it is Lorentz-and-CPT-invariant - as fits of course a fundamental theory.

I have shown in detail[13] that the relativistic quantum theory, either in its second quantized version, or in the first quantized version I have proposed[14], allows a perfect formalization of the EPR correlations either proper, displaying "non separability of measurements issuing from a common preparation", or reversed, displaying "non separability of preparations converging into a common measurement".

So it finally turns out that if (as Einstein rightly pointed out in 1927) the distant EPR correlations are indeed incompatible with the 1905 macrorelativity theory (where the causality concept is conceived as arrowed from past to future), they are completely consistent with the 1952-56 microrelativity theory, where the causality concept is conceived as CPT-invariant.

III - CPT-INVARIANCE AS GENERALIZED LOSCHMIDT T-INVARIANCE

Had Loschmidt imagined his colliding molecules as ogival rotating rifle bullets, that is, as projectiles where fore and aft, right and left, make sense, he would have been led to a CPT- rather than to a T-invariance principle. This we can explain by means of a little fable.

For reasons appearing later, we consider that a printed movie film is a spacetime object. Two symmetry operations are possible: running the film backwards, which we denote T, and call time reversal, and turning the film upside-down, or recto-verso, which we denote P, and call space or parity reversal.

If the original sequence displays, say, an automobile entering a garage backward, the T-reversed sequence displays an automobile coming forward out of a garage. Let us call particle a car moving forward, antiparticle a car moving backward, and denote C particle-antiparticle exchange. Let us also call emission coming out, and absorption going in a garage. By CT = 1 we mean that emission of a particle and absorption of an antiparticle (or vice versa) are two faithful images of the same space-time object: the printed film. However, an other assumption has been implicitely made: P-invariance, as a similar argument holds with the film turned recto-verso.

As just defined, our particle-antiparticle concept is certainly incomplete, because both a particle and an antiparticle are (in some sense) spatial "objects", and should be distinguishable from each other in a static situation. Having an automobile at rest, how do we exchange fore and aft without affecting its transverse sections? By a parity reversal. So we are naturally led to assume that CP = 1 holds under the assumption of T-invariance.

Combining both arguments we end up with CPT = 1, meaning that it is by turning the film upside-down and running it backwards that we exchange in general emission of a particle and absorption of an antiparticle (or vice versa). So the PT operation, which Pavsic and Recami[11] call "external space-time reversal", and I have termed[12] covariant motion reversal, exchanges screwing-in a right handed screw with screwing-out a left handed screw. By CPT = 1 we mean that particle-antiparticle exchange C (at emission or absorption) and covariant motion reversal PT are mathematically equivalent to each other.

Now we want to think in terms of 4-dimensional Minkowski diagrams, denoting x, y, z, ct the spacetime coordinates of a vehicle the shape of which we disregard. Going from kinematics to dynamics we have a simple, synthetic, recipe for distinguishing at one stroke fore and aft, right and left: rest mass reversal, $m \rightleftharpoons -m$, in the formula[15]

$$p^i = mu^i \qquad (1)$$

connecting the momentum-energy p^i to the 4-velocity u^i ($u_i u^i = - c^2$). This is the basis of the well known Stückelberg-Feynman interpretation of particle-antiparticle exchange, and, indeed, the deepest and most general formalization of it[16,11,12]. The accepted convention is that particles have a positive and antiparticles a negative rest mass[17].

Figures 1 display, using the Stückelberg-Feynman algorithm in the momentum-energy representation, and the example of the $e^+e^- \rightleftharpoons 2\gamma$ transition, the C (Fig. 1a and 1b), the PT (Fig. 1b and 1c) and the CPT (Fig. 1a and 1c) symmetries. These figures show that (disregarding, for brevity of speech, Heisenberg's uncertainty relations) the covariant motion reversal PT corresponds to the Pavsic-Recami "external spacetime reversal", the particle antiparticle exchange C to their "internal spacetime reversal", and the identity operation CPT to overall geometrical spacetime reversal, which I have denoted $\Pi\theta$[12]. It is almost self evident that fundamental physical laws must have, in a 4-dimensional geometrical theory, the

$$\Pi\theta = CPT = 1 \qquad (2)$$

invariance. So, after the Einstein gravity concept, and the Einstein-de Broglie equivalence between 4-frequency and momentum-energy, the C^{-1} = PT equality is the third example of a direct coupling between physics and geometry.

The final touch of CPT invariance consists of the labeling of the external lines in Fig. 1: $\bar{\Psi}$ means either emitting a particle or absorbing an antiparticle (and the reverse for Ψ). This is essential to second quantization. It is at the root of the C and PT equivalence. It is con-

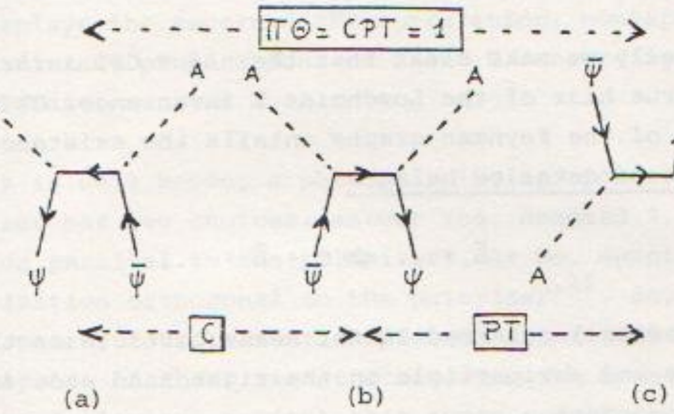

Fig. 1.

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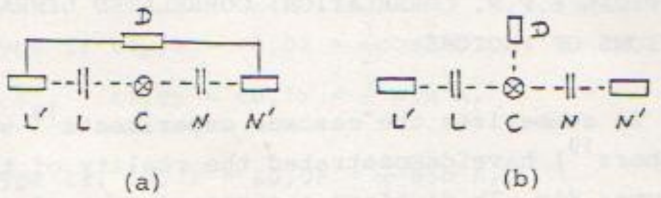

Fig. 2.

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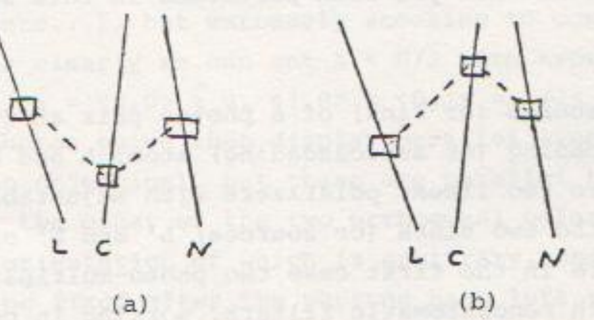

Fig. 3.

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spicuous in the $\Pi\ \theta$ symmetry, and is instrumental in the efficacy of the Feynman algorithm.

Finally we make clear that the $\Pi\theta$ = CPT invariance is the true heir of the Loschmidt T invariance. CPT invariance of the Feynman graphs entails the existence of a <u>principle of detailed balance</u>

$$A + \bar{B} + \ldots \rightleftharpoons C + \bar{D} + \ldots \tag{3}$$

where (beware!) a barred letter means particle on the left hand side and antiparticle on the right hand side (and vice versa of course).

IV - A TYPICAL E.P.R. CORRELATION: CORRELATED LINEAR POLARIZATIONS OF PHOTONS

Fig. 2a summarizes the cascade experiments[18] which (among others[19]) have demonstrated the reality of the EPR correlations; Fig. 2b displays a reversed type of experiment using anticascade, or "échelon absorption" processes, of a kind which has become routine since the advent of the dye laser, but has not yet been performed in this specific form[20].

The source (or sink) of a photon pair at C is a three-level cascading (or anticascading) atom; L and N, aligned with C, are two linear polarizers with adjustable relative angle A; the two sinks (or sources) L' and N' of the photons are in the first case two photo-multipliers associated with monochromatic filters, working in coincidence, and, in the second case, low intensity dye lasers[21].

The first experiment displays the EPR correlation proper, nonseparability of two distant measurements at L and N issuing from a common preparation at C; the second one displays the reversed EPR correlation, nonseparability of two distant preparations at L and N converging into a common measurement at C.

As is well known, a photon impinging upon a linear polarizer has two choices: answer Yes, denoted 1, "polarization parallel to the polarizer", or No, denoted 0, "polarization orthogonal to the polarizer"[22]. So, for our photon pairs, four transition probabilities (all deducible from any one of them) are at stake. Quantum mechanics shows (see the following section) that there are two, and only two, types of cascades or anticascades, with the corresponding transition probabilities:

$$\text{Type I: } \langle 1,1\rangle = \langle 0,0\rangle = \tfrac{1}{2}\cos^2 A, \quad \langle 1,0\rangle = \langle 0,1\rangle = \tfrac{1}{2}\sin^2 A, \tag{4}$$

$$\text{Type II: } \langle 1,1\rangle = \langle 0,0\rangle = \tfrac{1}{2}\sin^2 A, \quad \langle 1,0\rangle = \langle 0,1\rangle = \tfrac{1}{2}\cos^2 A \tag{5}$$

This is mathematically quite pleasing (rotationally invariant etc...), but extremely shocking to common sense. To see this clearly we can set $A = \Pi/2$ with type I cascades, so that $\langle 1,1\rangle = \langle 0,0\rangle = 0$, $\langle 1,0\rangle = \langle 0,1\rangle = 1/2$: all measured photon pairs then display parallel linear polarizations (no objection), but these are parallel to either the one or the other of the two orthogonal polarizers the (overall) orientation of which is arbitrary, and could in principle be fixed after the photons have left the source[23]! So, as previously said, "the correlated dice are cast not when shaken together inside the cup C, but when they stop on the table at L and N"!

Consider now the reversed procedure: common sense accepts quite easily that all absorbed[21] photon pairs "have" parallel linear polarizations, and that these were given by the polarizers; common sense does not object either at the possibility of turning the polarizers while the photons are in flight from L and N to C, as it believes that each photon does "retain" the polarization that has been "imparted" to it!.

Also, that the direct correlation is not spoiled if the distances CL and CN are made very large[24] looks very paradoxical, but one feels it trivial that the reversed correlation is then not.

The unavoidable conclusion of all this is that we are completely misled by our natural feeling that causality is retarded. While retarded causality is exemplified in the reversed, advanced causality is no less clearly displayed in the direct EPR correlations. Putting things together, what turns out is that causality is arrowless at the micro-level - a statement already implicit in Loschmidt's 1876 reversibility argument, to be sharpened in the next Section.

V - LORENTZ-AND-CPT-INVARIANCE OF THE EPR TRANSITION AMPLITUDE FOR PHOTON PAIRS

Figures 3a and 3b display, in the (x, ct) plane [or rather, in the Fourier associated (k_x, ν/c) plane] the spacetime trajectories [or rather, the energymomenta] of the flying photon pairs and of the preparing and measuring devices at C, L, N. The very concise following derivation uses the (Lorentz and CPT invariant) S-matrix scheme. The square boxes at C, L, N, emphasize that what counts, in this scheme, is the definition of the preparing and measuring devices while the particles go through them (what they are before or after being irrelevant).

The Lorentz-and-CPT-invariant transition amplitude comes out straightforward as invariant with respect not only to the (spatial and temporal) distances CL and CN (and thus to the time ordering of the measurements or preparations at L and N) but also to the relative velocities of C, L, N. So, the headaches and confused complaints which the EPR correlations have caused are all cured straightaway by the sort of aspirin named S-matrix[25] - leaving to a cleared mind the sole problem of a straightforward interpretation of the formulas.

Our two photon problem belongs to quantum electrodynamics, where the transition amplitude, being C, P and T invariant, is a scalar[26]. Relativistically speaking, what is measured (or prepared) at L and N is a pair of electromagnetic field strengths $|H_L^{ij}>$ and $|H_N^{ij}>$. The source (or sink) at C of the pair we idealize as a spin zero particle, either scalar $|\varphi>$ or pseudoscalar $|\varphi\varepsilon_{ijkl}>$. So, the two possible expressions of the (L and N symmetric) transition amplitude are (up to normalizing factors)

$$<\varphi|H_L^{ij}>|H_{ij}^N> \quad \text{or} \quad <\varphi\varepsilon_{ijkl}|H_L^{ij}>|H_N^{kl}>, \qquad (6)$$

that is, in prerelativistic notation and Gaussian units, and dropping for simplicity the bra and ket notation,

$$\bar{\varphi}(\vec{E}_L \cdot \vec{E}_N - \vec{H}_L \cdot \vec{H}_N) \quad \text{or} \quad \bar{\varphi}(\vec{E}_L \cdot \vec{H}_N + \vec{H}_L \cdot \vec{E}_N). \quad (7)$$

Taking the axes x and ct inside the plane of the three energy-momenta, so that the photons fly oppositely, denoting A the angle between the polarizers, and normalizing, we get the (x, ct Lorentz invariant) transition amplitudes

$$(1/\sqrt{2}) \cos A \quad \text{or} \quad (1/\sqrt{2}) \sin A \qquad (8)$$

fitting exactly the transition probabilities (4) and (5), respectively.

Adjustable parameters exist at L and N, but not at C. Thus, if causality has any operational meaning, the inherent Lorentz-and-CPT-invariance of the preceding formulas does show that causality is arrowless at the microlevel.

So, the relativistic S-matrix scheme does have the full theory of the EPR correlations (either proper or reversed). And so, the so-called "paradox"[2] in these (if any) is none else than a quantal and relativistic extension of the 1876 Loschmidt statistical paradox.

VI - OTHER IMPLICATIONS OF THE S-MATRIX SCHEME

Nonseparability of spatially distant preparations or measurements, as physically and mathematically tied via Feynman zigzags[27], is thus born from the union of two earlier "paradoxes": the 1926 Born wavelike probability calculus, and the 1952-56 CPT-invariance.

As implied in the Feynman systematization, it belongs (modulo a specific further remark) to the extended space-time philosophy of Minkowski and Fokker[28]. The transition amplitude, by its use of propagators (either in its space-time or its 4-frequency representation) ignores all spurious difficulties tied with time ordering; also, it displays directly its essential symmetry in the partial preparations and in the partial measurements.

For one thing its use discards the frequently found, but extremely shocking, statement that "the first in time of two distant measurements instantaneously collapses the other subsystem into the strictly associated state". Such a statement is neither relativistically covariant, nor symmetric in the two measurements, while the formulas are both. This statement is also self contradicting in the following sense: if the two measurements are simultaneous (which is allowed, if no energy measurement is performed[29]) and do not match each other (as, say, two linear polarizations of arbitrary angle A), which of the two measurements collapses the other substate?

What must not be forgotten is that we are dealing with a conditional probability problem: the transition amplitude holds iff each incoming particle is prepared, and each outgoing particle is measured, as is written down in the formula[30]. It should be remembered that isomorphism between the formalism and its interpretative discourse is the hall mark of a sound theory[31].

So, the concept of the evolving state vector [$|\Phi(\sigma)\rangle$, in the Tomonaga-Schwinger relativistic formalism] is useless and misleading[32,33]. As it is untestable[34] it is useless: only the initial preparation $|\Phi\rangle=\Pi|\varphi\rangle$ and the final measurement $|\Psi\rangle=\Pi|\psi\rangle$ are tested. Inbetween, the evolving quantum system is neither in the retarded $|\Phi_\sigma\rangle=|U_{\sigma 1}\Phi_1\rangle$, nor in the advanced $|\Psi_\sigma\rangle=|U_{\sigma 2}\Psi_2\rangle$ state, because it is transiting between $|\Phi_1\rangle$ and $|\Psi_2\rangle$. Thus it is not "inside" spacetime (nor "inside" the 4-frequency space). Only the preparing and measuring devices, being macroscopic, can, to that extent, be thought of as located inside spacetime - itself a macroscopic concept.

According to the formula of the transition amplitude $\langle\Psi|\Phi\rangle=\langle\Phi|\Psi\rangle^*$, everything goes on as if the evolving system is symmetrically feeling the retarded influence of the preparation and the advanced influence of the measurement[35].

And, of course, the fact that $|\langle\Phi|\Psi\rangle|^2$ is read either predictively or retrodictively[36] is an expression of the Loschmidt kind of T reversibility[37].

An other frequent misconception that should be explicitely discarded is the one according to which there is a causal asymmetry built-in the definition of the Feynman propagator. Let us recall the expressions[38] of the Jordan-Pauli D and the Feynman D_F propagators in terms of the positive and negative frequency contributions D_+ and D_-, and of the retarded and advanced propagators D_R and D_A:

$$D = D_+ - D_- = D_R - D_A, \tag{9}$$

$$D_F = D_R + D_- = D_A + D_+. \tag{10}$$

As, outside the lightcone[39],

$$D = D_R = D_A = 0, \qquad D_+ = D_-, \tag{11}$$

one can, following Feynman, say that $D_F = D_-$ if $t<0$ and $D_F=D_+$ if $t>0$. But <u>this does not imply any causal asymmetry</u>! Covariantly speaking, let us denote C the $D_+ \rightleftarrows D_-$ and T the $D_R \rightleftarrows D_A$ exchanges; D and D_F have the symmetries[40]

$$D: \qquad P = - T = - C = 1, \tag{12}$$

$$D_F: \qquad P = CT = 1. \tag{13}$$

It may well be that the misunderstanding comes from the fact[41] that use of the Feynman propagator for describing the virtual particles automatically entails the exponential decay of higher energy levels. But this entirely stems from use of a predictive calculation. A "blind" retrodictive calculation would symmetrically yield an exponential build-up of the higher energy levels!

VII - ADDITIONAL INFORMATIONS

The contents of this Section have not been included in the main argumentation of our paper, which is thus more barely displayed to the reader. However they add some significant branches to the trunk of the tree.

Section V has presented a very concise S-matrix derivation of the transition amplitude for the emission (or absorption) of correlated spin 0 photon pairs. What then for the similar problem concerning spin 1/2 fermion pairs obeying the Dirac equation? The very same argument as in Section V shows that (up to normalizing factors) two transition amplitudes are then possible, the scalar $\bar{\varphi}\psi$ or the pseudoscalar $\bar{\varphi}\gamma_5\psi$, where $\bar{\varphi}$ denotes (say) the absorption of an antifermion and ψ that of a fermion (the "lepton number" being conserved). These are traditionally denoted ↑↓+↓↑ and ↑↓-↓↑, respectively, and, in the matrix representation originally used by Dirac, they assume the expressions

$$\bar{\varphi}\,\psi = \varphi_1^*\psi_1 + \varphi_2^*\psi_2 - \varphi_3^*\psi_3 - \varphi_4^*\psi_4 \,,$$
$$\bar{\varphi}\gamma_5\psi = \varphi_1^*\psi_3 + \varphi_2^*\psi_4 - \varphi_3^*\psi_1 - \varphi_4^*\psi_2 . \qquad (14)$$

The explicit calculation is easier in the rest frame of the system, where fermion and antifermion, endowed with the same rest mass m and the same energy w, have opposite momenta $\pm\vec{p}$[42]. As is well known, the "small components" ψ_1, ψ_2, of the fermion, and φ_3, φ_4, of the antifermion, are expressible in terms of the "large" ones, ψ_3, ψ_4, and φ_1, φ_2, so that a simple calculation yields[43]

$$\bar{\varphi}\,\psi = \text{zero times } (\varphi_1^*\psi_3 - \varphi_2^*\psi_4) \equiv 0,$$
$$\bar{\varphi}\gamma_5\psi = (m^2/w^2)[\varphi_1^*\psi_3 + \varphi_2^*\psi_4] \neq 0. \qquad (15)$$

that is, $\pm\vec{\beta}$ denoting the opposite velocities of the particles,

$$\bar{\varphi}\psi = \text{zero times } \beta(\uparrow\downarrow+\downarrow\uparrow) = 0, \qquad (16)$$
$$\bar{\varphi}\gamma_5\psi = (1-\beta^2)[\uparrow\downarrow-\downarrow\uparrow] \neq 0.$$

These formulas are "spatially isotropic", that is, they are invariant with respect to the angle between the momenta $\pm\vec{p}$ and the axis z selected, in the Dirac representation, for displaying the eigenfunctions "spin up", φ_1 and ψ_4, and "spin down", φ_2 and ψ_3. So, if $\vec{p}$ is along z, the discussion is in terms of the helicities; and, if $\vec{p}$ is orthogonal to z, it is adapted to a Stern-Gerlach type of experiment. As $\bar{\varphi}\gamma_5\psi$ decreases and goes to zero when β increases from 0 to 1, the extreme relativistic fermion and antifermion have opposite pure helicities.

Apart from these remarks, the fundamental point is that, by using the sole argument of relativistic covariance, without any explicit appeal to Pauli's exclusion principle, we have derived the accepted result for spin 0 fermion pairs.

Together with the contents of Section V, this indeed is a strong refutation of the (erroneous!) statement that the EPR correlation is a non-relativistic phenomenon.

Other relativistically covariant developments are significant, but, as I could not present them here without quoting verbatim a careful presentation I have recently given, I must refer the reader to the corresponding publication[44]. What they consist of is essentially this: I: an abstract formalization of "generalized ennuple Einstein correlations"[45]; II: a manifestly covariant formalism of first quantization (Fourier transforms, propagators, etc...) for free particles; III: a covariant presentation of the "position and polarization measurement" of a free particle, as significant in the EPR correlation experiments, the corresponding eigenfunction being the Jordan-Pauli propagator, thus implying arrowlessness of the causality concept.

VIII - CONCLUDING REMARKS

Concerning the EPR correlations the following statements (or equivalent ones) have been so widely issued and circulated that no explicit references are needed:

I - "The phenomenon of EPR correlations is (to say the least) not fully consonant with special relativity".

II - "The first in time of the two distant measurements instantaneously collapses the other subsystem into the strictly associated state".

III - "There is a causality asymmetry built-in the very definition of the Feynman propagator".

In the present paper it has been shown, however, that:

I - A perfect formalization of the EPR correlations, either proper or reversed, exists, which is manifestly Lorentz-and-CPT-invariant.

II - Irrespective of time ordering, the correlation formula is symmetric in the two measurements (EPR proper) or preparations (reversed EPR) L and N, be they compatible or not (in the quantal sense). Moreover, as is obvious in the S-matrix formula, and is demonstrated in experiments where the distances between L, N and the common preparation (EPR proper) or measurement (reversed EPR) C are varied, the Feynman zigzag LCN is the link of the correlation.

III - The Feynman propagator has the symmetries P and CT, but no causal asymmetry stems from this. For example, its predictive or retrodictive use in the S-matrix entails an exponential decay or build-up, respectively, of higher energy levels.

So, the wording directly isomorphic to the formalism is that, at the microlevel, the causality concept is Lorentz and CPT invariant, and thus is arrowless. This is a "scientific revolution" going much further than Loschmidt's 1876 statistical T-invariance, because Born's 1926 wavelike probability calculus is now the ruler. So, the long range EPR nonseparability is of a nature quite different from, say, Newton's universal interaction.

Macroscopically speaking, CPT symmetry is largely obliterated by the two factlike asymmetries of preponderance of retarded over advanced actions and (to a lesser extent) of matter over antimatter. These two define the realm of validity of macrophysics - which would merely collapse in their absence. For this reason two CPT-associated Feynman graphs are displayed as framed pictures, because one cannot CPT-reverse the environment. It remains, however, that CPT-invariance underlies the whole working of the spacetime telegraph that quantum mechanics truly is, so that refined investigation of information exchange between the users of the network may well uncover specific aspects of nonseparability more or less akin to "the claims of the paranormal".

Born's 1926 wavelike probability calculus has an other consequence: as Fock[46] and Watanabe[47] have explained, quantum mechanics uses retarded waves in prediction and advanced waves in retrodiction[48], so that the two factlike asymmetries of wave retardation and of probability increase are linked together. This solves the famous Einstein-Ritz[49] controversy, where reciprocal rather than conflicting statements were at stake[50].

Most quantum mechanical textbooks state that, due to the finiteness of Planck's h, there exists a reaction of the measuring apparatus upon the observed system. But where should the severance between observer and apparatus be drawn[51]? By logical necessity such a reaction implies the observer, as argued also by Wigner[52] on the basis of symmetry arguments. Truly, such a reaction was implied already in the mathematical equivalence $N = k \, Ln2 \, I$ between a negentropy N and an information I, so that it follows from the finiteness of Boltzmann's k. The deepest expression of the irreversibility law is: macroscopic preponderance of the $N \rightarrow I$ over the $I \rightarrow N$ transition, contrasting the "hidden face" of information (organizing power) to its "obvious face" (gain in knowledge).

What comes in with Planck's h is Born's wavelike probability calculus, according to which the quantal sequence preparing-evolving-measuring replaces the cybernetical sequence coding-transmitting-decoding. But as, at the micro-level, the spacetime and the 4-frequency pictures are mutually exclusive, both loose their so-called objectivity. Space-time and its content of events has no more objectivity than the frequency aspect of probability; truly, it is indissolubly-objective-and-subjective. And, again, a pluridisciplinary study of nonseparability might well uncover unexpected facts.

Concluding, my view of the EPR correlations boils down to this: their formalization is entirely contained in relativistic quantum mechanics as it presently exists. But then, by simply translating the formulas into words, an extremely unfamiliar landscape is sketched.

In 1905 Lorentz and Poincaré, carrying the Tables with the relativistic Law explicitely written down, stopped just before the Promised Land, because they did not completely trust the Word. Einstein entered, having fell a high wall by the trumpet blast that "invariance of the velocity c is not inconsistent with the relativity principle" (his own words). But this was just the end of a long story. A paradoxical fact had been uncovered: non-additive composition law of light and matter velocities (Arago, 1818; Michelson, 1887). Ad hoc formulas had been put forward (Fresnel, 1818; Fitzgerald, 1893). Then a synthetic, but paradoxical, formalism, implying the existence of a spacetime metric, was set up by Lorentz and Poincaré[53]. And finally Einstein uncovered the Sense of the Scriptures by plainly reading what was written down, Minkowski producing the Ark of the Covenant.

This is a very good example to ponder upon. In dictionaries the meaning n° 1 of paradox is usually given as: a surprising, but perhaps true statement. Copernicus' heliocentrism may be proposed as an example. It seems that the "EPR paradox" is of this very radical sort.

NOTES AND REFERENCES

1 A. Einstein, B. Podolsky and N. Rosen, Phys. Rev. 47 (1935), p.777.

2 As it seems, the wording "EPR paradox" is due to Einstein in P.A. Schilpp (ed), Albert Einstein, Philosopher Scientist, Evanston (Ill.), The Library of Living Philosophers, 1949, p.681.

3 A. Einstein, in Rapports et discussions du Cinguième Conseil Solvay, Paris, Gauthier Villars, 1828, pp. 253-256.

4 The probability concept is inherent in the seminal thinking of both Planck and Einstein concerning quantum mechanics, where the wave concept is inherent also. A careful historical research might be rewarding in this respect.

5 This point is emphasized in the famous 1965 Bell theorem, stressing a specific incompatibility between the classical and the new wave-mechanical probability calculus.

6 O. Costa de Beauregard, C.R. Acad. Sci. 236 (1953), p. 1632.

7 More precisely, in the second quantization conceptualization, it can carry the occupation number 0 - as was the case in Einstein's[3] original discussion.

8 This is an essential point: a transition amplitude can be read either predictively or retrodictively. This is at the root of the famous 1876 "Loschmidt paradox".

9 More precisely they are now known to be CPT-symmetric: see Section III below.

10 O. Costa de Beauregard, Phys. Rev. Lett. 50 (1983), p. 867.

11 E. Recami and W.A. Rodrigues, Found. Phys. 12 (1982), p. 709 (referring to previous work by Recami and coworkers); also M. Pavsic and E. Recami, "Charge conjugation and internal symmetries," Frascati Documents INFN-AE, (1982), 82/7.

12 O. Costa de Beauregard, Found. Phys. 12 (1982), p. 861.

13 O. Costa de Beauregard, Nuovo Cim. 42B (1977), p. 41 and Nuovo Cim. 51B (1978), p. 267; Physis 22 (1980), p. 211.

14 O. Costa de Beauregard, Précis de Mécanique Quantique Relativiste, Paris, Dunod 1967 (synthesis of previous papers).

15 As is well known, momentum and velocity of spinning particles may be noncollinear. It remains true, however, that under rest-mass reversal the scalar product $p^i u_i$ changes its sign. See in this respect my discussion of the Dirac electron case, ref. [12].

16 J. Tiomno, Nuovo Cim. 1 (1955), p. 226, is the proponent of this scheme. For a thorough discussion see J. Winogradski, Tensor 38 (1982), p. 109.

17 u^i is always taken as pointing inside the future light cone, so that p^i points into the "future" for particles and into the "past" for antiparticles.

18 The most recent and precise cascade experiments testing EPR correlations are those of the Aspect group: A. Aspect, P. Grangier and R. Roger, Phys. Rev. Lett. 47 (1981), p. 460 and Phys. Rev. Lett. 49 (1982), p. 91; A. Aspect, J. Dalibard and R. Roger, Phys. Rev. Lett. 49 (1982), p. 1804. Reference to previous experimental work is found in these papers.

19 Significant experiments using the $e^+e^- \rightarrow 2\gamma$ transition have been performed: L.R. Kasday, J.D. Ullmann and C.S. Wu, Nuovo Cim. 25B (1975), p. 633; A.R. Wilson, J. Lowe and D.K. Butt, J. Phys. G. 2 (1976), p. 613; W. Bruno, A. d'Agostino and C. Maroni, Nuovo Cim. 40B (1977), p. 143; G. Bertolini, E. Diana and A. Scotti, Nuovo Cim. 63B (1981), p. 651.

20 There do exist, however, experiments displaying a reversed EPR correlation in the form of nonseparability of occupation numbers at emission of interfering low intensity laser beams: R.L. Pflegor and L. Mandel, Phys. Rev. 159 (1967), p. 1084 and J. Opt. Soc. Amer. 58 (1967), p. 946.

21 Of course, as there is a phase condition, the absorption occurs in pulses, but this does not really matter. Incidentally, this reversed experiment would yield an easy, fast and precise test of the correlation formula.

22 Both answers can be displayed in the same experiment if birefringent crystals (or their equivalent) are used as polarizers; the second experiment in ref.[18] is of this sort.

23 The third experiment in ref.[18] is of this sort.

24 This has been tested in the 1976 and 1977 experiments of ref.[19], and in the third experiment of ref.[18].

25 For example, the bizarre idea of some hidden signal, other than the one obviously tied by the particles themselves, looks like sheer nonsense in the S-matrix scheme. N.D. Mermin, Am. J. Phys. 49 (1981), p. 940 comments upon this from a different standpoint. See also O. Costa de Beauregard, Amer. J. Phys. 51 (1983), p. 513.

26 Pseudoscalar transition amplitudes also enter the general case.

27 It may seem at this point that there is some similarity between my interpretation of the EPR correlation and that of H.P. Stapp, Nuovo Cim. 29B (1975), p. 270. This similarity, however, is only superficial, as made clear by the numerous incompatibilities between the present paper and, e.g., H.P. Stapp, Found. Phys. 12 (1982), p. 363.

28 A.D. Fokker, Time and Space, Weight and Inertia, Oxford, Pergamon, 1965.

29 The detections of the photons at L and N are not proper energy measurements.

30 This is a specification of Bohr's statement that the definitions of the preparing and measuring procedures are an essential part of the phenomenon studied.

31 A typical example is of course Einstein's 1905 relativity theory as opposed to Lorentz's and Poincaré's.

32 Y. Aharonov, and D.Z. Albert, Phys. Rev. D21 (1980), p. 3316.

33 O. Costa de Beauregard, Lett. Nuovo Cim. 31 (1981), p. 43 and Lett. Nuovo Cim. 36 (1983), p. 39.

34 Trying to test it would contradict Bohr's statement referred to in ref.[30].

35 This somewhat revives the spirit of the Fermat and the Euler-Maupertuis-Hamilton extremum principles.

36 A typical retrodictive statistical reasoning occurs in Heisenberg's microscope thought experiment, where one infers from the final impact of a scattered photon either the initial position or momentum of the scattering electron, according as the object plane or the focal plane is aimed at: C.V. Weiszäcker, Zeits. f. Phys. 70 (1931), p. 114.

37 Reversibility of the transition amplitude or probability is also significantly stressed by W.C. Davidon, Nuovo Cim. 36B (1976), p. 34, and by J. Rayski, Found. Phys. 9 (1979), p. 217.

38 See for example J.M. Jauch, and F. Rohrlich, The Theory of Photons and Electrons, Cambridge, Mass., Addison Wesley, 1955, pp. 419-424.

39 This allows to close the integration contour defining the various D propagators either above or below the real axis for x spacelike, thus preserving relativistic covariance.

40 The C or T symmetry exchanges D_F with the anti-Feynman propagator $D_{AF} = D_R - D_+ = D_A - D_-$.

41 See ref.[38] pp. 408-410.

42 This is classical parlance! In the Stückelberg-Feynman scheme they have the same momentum, but opposite rest-masses and velocities.

43 Of course, under the parity symmetry $\varphi \rightleftarrows \gamma_4\varphi$, $\psi \rightleftarrows \gamma_4\psi$, the parenthesis is preserved and the bracket changes sign.

44 Proceedings of the 1983 Tokyo ISQM Conference, to be published as a special issue of Prog. Theor. Phys. See Sections VII, VIII and IX.

45 The original mathematical recipe (without discussion of relativistic covariance) was by A. Garuccio and F. Selleri, Nuovo Cim. 36B (1976), p. 176.

46 V. Fock, Dokl. Akad. Nauk SSSR 60 (1948), p. 1157.

47 S. Watanabe, Rev. Mod. Phys. 27 (1955), p. 26.

48 J. von Neumann's deduction of quantal entropy increase rests on use of retarded waves.

49 A. Einstein, and W. Ritz, Phys. Zeitsch. 10 (1910), p. 817.

50 While Einstein's photon was already known, L. de Broglie's matter wave was not. So it was not yet obvious that particle scattering and wave scattering do go hand in hand.

51 J. von Neumann, as is well known, has analyzed this point.

52 E.P. Wigner, Symmetries and Reflections, Cambridge, Mass, M.I.T. Press, 1967, pp. 171-184.

53 H. Poincaré, Rendic. Circ. Mat. Palermo 21 (1906), p. 129, is the promoter of the spacetime concept.