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Lorentz and *CPT* Invariances and the Einstein-Podolsky-Rosen Correlations

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The S-matrix scheme allows a straightforward formalization of the Einstein-Podolsky-Rosen nonseparability either of distant measurements issuing from a common preparation, or of distant preparations converging into a common measurement. This implies Lorentz and CPT invariance of the causality concept at the elementary level, which is a quantal and relativistic extension of the 1876 Loschmidt reversibility statement.

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Deep theoretical issues concerning the Einstein-Podolsky-Rosen (EPR) correlations have been pondered recently in this Journal,[1] not including, however, the one to be considered here, which is still unsettled.[2]

As I have shown in detail[3] that the S-matrix formalism yields a straightforward Lorentz- and CPT-invariant formalization of the Einstein-Podolsky-Rosen[4] correlations either proper (nonseparability of measurements issuing from a common preparation) or reversed (nonseparability of preparations converging into a common measurement), I present here a special derivation, along this line, of the transition amplitude for correlated linear polarizations of spin-0 photon pairs either emitted from an atomic cascade or absorbed into an anticascade ("echelon absorption").

The source or sink of the photon pair will be idealized as a spin-0 scalar, $|\varphi\rangle$, or pseudoscalar, $|\varphi\epsilon_{ijkl}\rangle$, particle. The twin polarization measurements (respectively, preparations) performed at a and b are those of electromagnetic field strengths $|H_a{}^{ij}\rangle$ and $|H_b{}^{ij}\rangle$. The transition amplitude (in this C-, P-, and T-conserving transition) is a scalar, the two possible expressions of which are (up to normalizing factors)

$$\langle\varphi_0|H_a{}^{ij}\rangle\,|H_{ij}{}^b\rangle \quad\text{or}\quad \langle\varphi_0\epsilon_{ijkl}\,|H_a{}^{ij}\rangle\,|H_b{}^{kl}\rangle, \quad (1)$$

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

$$\overline{\varphi}_0(\vec{E}_a\cdot\vec{E}_b-\vec{H}_a\cdot\vec{H}_b) \quad\text{or}\quad \overline{\varphi}_0(\vec{E}_a\cdot\vec{H}_b+\vec{H}_a\cdot\vec{E}_b). \quad (2)$$

Taking the axes x and ct inside the plane of the three energy-momenta, so that the two photons fly oppositely, denoting by α the angle between the vectors $\vec{E}_a$ and $\vec{E}_b$, or $\vec{H}_a$ and $-\vec{H}_b$, and normalizing, we rewrite expressions (2) in the familiar form

$$(1/\sqrt{2})\cos\alpha \quad\text{or}\quad (1/\sqrt{2})\sin\alpha. \quad (3)$$

Adjustable parameters exist at a and b, but not at O. What counts, in the S-matrix scheme, is the setting of the preparing and measuring devices while the particles go through (what they are before or after being irrelevant). This, together with the insensitivity of the transition amplitude to the (spatial and temporal) distances Oa and Ob, is felt as "trivial" in the reverse, but "paradoxical" in the direct EPR correlation (where it has been tested[5]). In other words, retarded causality looks natural and advanced causality paradoxical. However, both the phenomenology and the mathematics of the EPR correlation

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show that causality is CPT and Lorentz invariant at the elementary level. This is a quantal and relativistic extension of the 1876 Loschmidt reversibility argument needing some comments.

Two recent papers[6,7] have independently stressed the $\Pi\Theta = CPT$ equality, where C denotes particle-antiparticle exchange, PT covariant motion reversal, and $\Pi\Theta$ geometrical reversal of all four space-time axes. Topological invariance of the Feynman graphs displays directly this interesting binding between physics and geometry.

Concerning the causality concept, Recami and Rodrigues,[6] following Feynman,[8] use a "fundamental postulate" according to which a "negative-energy particle moving backwards in time" is "reinterpreted" as a "positive-energy antiparticle moving forward in time." The mathematical basis for this consists in the well-known expressions of the Jordan-Pauli D and the Feynman D_F propagators,

$$D = D_+ - D_- = D_R - D_A, \qquad (4)$$

$$D_F = D_R + D_- = D_A + D_+, \qquad (5)$$

in terms of the positive- (D_+) and negative-energy (D_-) propagators, and of the retarded (D_R) and advanced (D_A) propagators, together with the fact that, outside the light cone,

$$D = D_R = D_A = 0, \quad D_+ = D_- . \qquad (6)$$

So, given an inertial frame, there hold the formulas $D_F = D_+$ if $t > 0$ and $D_F = D_-$ if $t < 0$. But, of course, the intrinsic symmetries of the Feynman propagator are not magically changed by selecting for convenience a spacelike plane.

I prefer using a wording that is completely frame-of-reference free, and that stresses the two quite obvious mathematical symmetries of retarded and advanced causality ($D_R \rightleftarrows D_A$) and of positive and negative energies ($D_+ \rightleftarrows D_-$). When concluding, I will briefly discuss the "generalized Loschmidt paradox" stemming from this.

Now, a transition amplitude such as (1) or (2) is *conditional:* It holds *if* each and every one of the incoming particles *is* prepared, and each and every one of the outgoing particles *is* measured, *as is written down in the formula.* This formalizes Bohr's well-known statement that the definition of the preparing and measuring devices is an essential part of the phenomenon studied. Be it as it may, these important, and well-known, statements, have been overlooked in quite a few presentations of the EPR correlations, as I explain now.

Expressions (2) may be rewritten as

$$(1/\sqrt{2})(Y_a Y_b + Z_a Z_b) \quad \text{or} \quad (1/\sqrt{2})(Y_a Z_b - Z_a Y_b), \qquad (7)$$

with Y and Z denoting orthogonal linear polarization directions. When read carelessly, these (or similar) formulas have been very often interpreted as saying that "the first" in time (say, a) of the two distant measurements "instantaneously collapses" the other subsystem b, into the associated state. Such a statement is very shocking in three aspects. First, it is not symmetric in a and b, and second, it is not relativistically covariant, while the formulas are both. Third, it is self-contradicting in the following sense: If, in some frame, the two measurements are exactly simultaneous (which is allowed, if no energy measurement is performed) and do not match each other (as, say, two linear polarization measurements of angle $0 \neq \alpha \neq \pi/2$) then, *which of the two measurements collapses the other substate?* What has been forgotten is, of course, that a word "*if*" is attached to *both* measurements, at b no less than at a. It should be remembered that isomorphism between the formalism and its interpretative discourse is the hallmark of a sound theory.[9]

The Lorentz- and CPT-invariant concept of the *transition amplitude* renders useless the *untestable* idea that the "evolving system" *is in* the time-dependent, retarded, state prepared as $|\Phi\rangle$ (any more than it *is in* the advanced state measured at $|\Psi\rangle$). Thus, it not only eliminates all reference to time ordering, but also emphasizes again the arrowlessness of the microcausality concept.

When Einstein[10] in 1927 (apropos of the distant correlation) very rightly pointed to a conflict between the "new" quantum mechanics and his 1905 relativity theory (obeying orthochronous Lorentz invariance and retarded causality), he did not foresee the advent of a new, CPT-invariant, microrelativity theory matching quantum mechanics, which is clearly illustrated in the EPR correlations. This is the "generalized Loschmidt paradox" which has been alluded to; it consists of the fact that *two CPT-associated Feynman graphs are always displayed as "framed pictures," because one cannot CPT-reverse the laboratory equipment.*

It is today quite clear that the thermodynamical and statistical time arrow is, in Mehlberg's[11] words, "factlike and not lawlike"; Boltzman[12] himself had excellently made that point. A similar statement holds regarding retarded and advanced waves, and Fock[13] and Watanabe[14] have shown that, in the Born wavelike probability calculus of quantum mechanics, both statements are reciprocally connected; this solves the famous 1906–1909 Einstein-Ritz controversy. Concerning the question of causality as raised by Recami and Rodriques,[6] it is well known[15] that use of the Feynman propagator for describing virtual particles entails, if used in prediction, the exponential decay of higher energy levels, and, if used in "blind" retrodiction,[14] their buildup.

Analogous statements hold for the factlike, macroscopic preponderance of particles over antiparticles. Macrophysics is *defined* as obeying *both* of these asymmetry statements, because it would merely collapse in their absence. However, an adequate discussion of the whole matter would need a long paper, as the *negentropy-information* equivalence would come into the picture, together with the quantum measurement problem. In this respect, penetrating remarks by Wigner[16] should be pondered.

Eberhard[17] has stated that, in the EPR correlations problem, either quantum mechanics, or relativity theory, or the existing causality concept will have to yield. The fact is that the correlation does exist, vindicating the quantum theory, *and* is formalizable in a way that is straightforward and Lorentz and *CPT* invariant.

So, it finally turns out that the "EPR paradox" precisely consists of the *CPT* invariance of the causality concept at the elementary level, which is a quantal and relativistic generalization of the classical Loschmidt *T* invariance.

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