THE 1927 EINSTEIN AND 1935 EPR PARADOX *

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SUMMARY. — The distant Einstein correlation exists both as a *predictive correlation between future measurements* and as a *retrodictive correlation between past preparations.* Various experiments using polarizations have shown the first phenomenon, while Pflegor and Mandel's interference experiments using two laser beams have illustrated the second one. A synthetic presentation of both phenomena using the Schwinger-Feynman S-matrix formalism is given, showing that *they belong to the scheme of relativistic quantum mechanics.*

The so-called Einstein paradox is thus shown to be born from the union of two earlier paradoxes: 1) *intrinsic time symmetry*, as discussed by Loschmidt and Zermelo in classical statistical mechanics; 2) *Born's principle of adding partial amplitudes* rather than probabilities, forbidding to think of micro-entities as *objects* separately *endowed* with *properties.*

The Feynman zigzag thus appears as the *deus-ex-machina* of the Einstein correlation, and as the wizard of the Einstein paradox. The macroscopic retarded causality concept is then replaced, at the elementary level, by a *time-symmetric causality concept.*

Philosophical consequenses are briefly discussed.

I. *Introduction*

In 1927, at the 5th Solvay Council, over the very cradle of the « New Quantum Mechanics » of de Broglie, Schrödinger, Heinsenberg, Dirac and Born, Einstein [1] was clever enough to perceive a very unusual feature of the infant, and to cast upon him (for the worst and for the best) the malignant spell which came to be known as the 1935 Einstein-Podolsky-Rosen [2] paradox.

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[1] A. EINSTEIN, in *Rapports et Discussions du 5e Conseil Solvay*, Paris, Gauthier Villars 1928, p. 253.

[2] A. EINSTEIN, B. PODOLSKY and N. ROSEN, « Phys. Rev. », *47*, 777 (1935).

A *paradox*, according to dictionaries, is not what most people think. In its fundamental, or etymological meaning, a *paradox* is defined as a surprising, or even upsetting, but perhaps true statement. Copernicus' heliocentrism was once such a paradox. The fact is that the « scientific revolutions » as discussed by Kuhn [3] and, before him, by Duhem,[4] do proceed from the characterization of a paradox and (following heated discussions) the proclamation of a new *paradigm*.[5] In it the initial smoke has been turned into a dazzling light–and « normal science » [3] starts marching again.

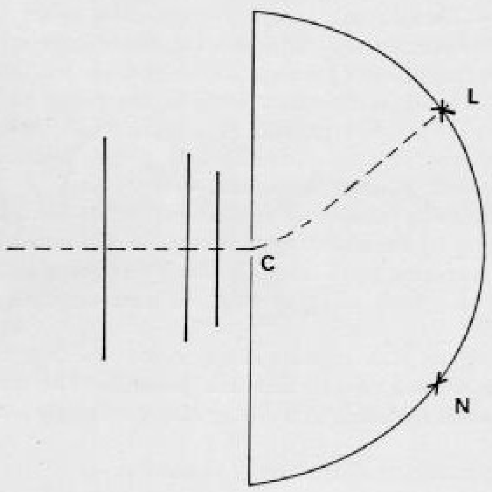

Fig. 1

What Einstein said in 1927 amounts to this. Suppose (Fig. 1) that a quantized wave carrying (for simplicity) just one corpuscle is diffracted by a small aperture C inside a plane screen, and that the corpuscle (say, a photon) subsequently blackens one grain, L, of a hemispheric plate centered at C. How does it happen, asked Einstein, that another grain, say N, is informed that it should not be blackened? Or, in the negative form of the argument later expressed by Rennin-

[3] T. S. KUHN, *The Structure of Scientific Revolutions*, Univ. of Chicago Press 1962; 2nd ed., 1970.

[4] P. DUHEM, *The Aim and Structure of Physical Theory*, Princeton Univ. Press 1954 (Translated from the French 1913 edition by P. Wiener).

[5] *Paradox and Paradigm*, R. G. Colodny ed., Univ. of Pittsburgh Press 1973.

ger,[6] if N is not blackened at a time when the photon has certainly been absorbed, how is the information drawn that another grain, say L, must have been blackened?

Of course, no paradox at all would exist if it could be stated that, so to speak, the dice have been cast at C. The point is that the very mathematics of the queer chance game that is at stake, as defined by Born in 1926,[7] definitely forbid that the dice are cast at C, and require that they are cast at L and/or N (wherever L and N are on the hemisphere). This is extremely disturbing, not only because, at first sight, a physical channel is lacking for telegraphing the information from L to N or *vice versa*, but also (as Einstein pointed out) because such an instantaneous information transfer would seem to violate a fundamental assumption of the relativity theory.

This puzzling problem was often discussed among de Broglie and his students, and once, around 1947, I pointed out that 1°) There is indeed a physical channel connecting the two detection events at L and N, the one through the past diffraction at C! 2°) That this channel, consisting of two timelike vectors, does not violate the relativistic principle excluding direct spacelike propagations. 3°) That of course such a correlation, if true, should violate Einstein's prohibition to « telegraph into the past light cone ». 4°) But that, after all, *intrinsic time symmetry* was a trait common to mechanics and to wave theory (either classical or quantal), not to speak of the mathematics of the probability theory itself.[8] At the moment de Broglie positively thought that I had become mad. A mathematical symmetry, said he, could not prevail against a physical certainty: causality could not go backwards in time, and Poincaré had irrefutably argued against the physical existence of advanced waves.

Anyhow, I have published my idea quite a few times[9] since 1953,

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[6] W. Renninger, « Physik » *158*, 417 (1960); « Phys. Zeits. », *136*, 251 (1963).

[7] This very scheme is implicit in A. Einstein, « Phys. Zeits. », *10*, 185 and 323 (1909), where the photon concept is discussed.

[8] The dissymmetry between predictive and retrodictive calculations, as expressed by the use of Bayes' conditional probabilities in retrodiction, is not inherent in the mathematics, but in the use one decides to make of the mathematics. It stems from the assumption of *retarded causality*, as implied in the very classical wording for retrodictive problems: « problems in the probability of causes ».

[9] O. Costa de Beauregard, « Comptes Rendus », *236*, 1632 (1953); « Rev. Intern. Philos. », *61-62*, 1 (1964); « Dialectica », *19*, 280 (1965); in *Proc. Intern. Conf. Thermodynamics*, P. T. Landsberg ed., Butterworth's, London 1970, p. 539; *Proc. Intern. Symp. Relativity Calcutta*, 1975-1976, p. 53; « Found. Phys. », *6*, 539 (1976); « Synthèse », *35*, 129 (1977); « Nuovo Cim. », *42B*, 41 (1977) and *51B*, 267 (1979).

and Davidon[10] and Stapp[11] have come to very similar ideas, which also spontaneously pop out in many discussions.[12]

For a better understanding of the nature of the problem and of the physics behind it I will present a little fable, the basic idea of which is de Broglie's.[13] Suppose (Fig. 2) that at 0^h GMT two travellers leave the Calcutta airport C, one for London L, and the other for Nagasaki N, each carrying a closed box which contains, or not, the one ball which a third man has enclosed, behind a veil. At 8^h GMT, having landed, each man opens his box, and immediately infers what the *other* one finds. There is nothing mysterious in this, as we are dealing with an elementary problem in information theory. This is because we are playing with the *classical*, and not the 1926 Born probability calculus. There *is* a so called « local hidden variable » which *has* the value 1 in one box and 0 in the other. The dice have been cast at C, but not looked at, so what changes at L and N is only a « subjective information »; the « objective negentropy » has changed at C.

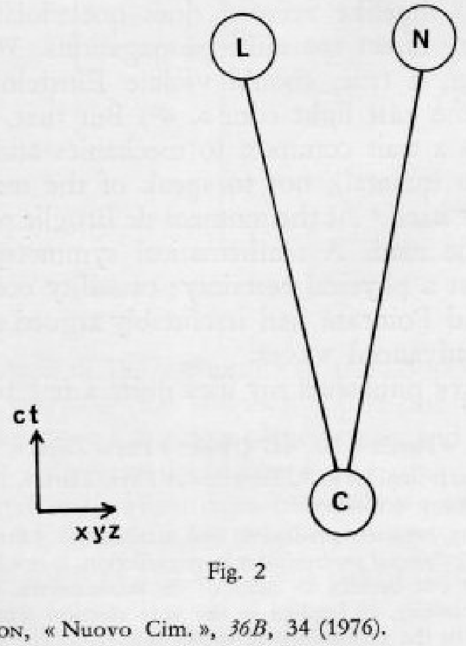

Fig. 2

[10] W. C. DAVIDON, « Nuovo Cim. », *36B*, 34 (1976).

[11] H. P. STAPP, « Nuovo Cim. », *29B*, 270 (1975).

[12] See for example J. F. CLAUSER and M. A. HORNE, « Phys. Rev. », *D 10*, 526 (1974) footnote 13.

[13] L. DE BROGLIE, *Etude critique ... de la mécanique ondulatoire*, Paris, Gauthier Villars 1963, p. 29.

As will be shown in the next section, this whole scheme undergoes a radical transmutation in the new *wavelike probability calculus* which Born defined in 1926, as the one consonant with the *wave mechanics* of de Broglie and Schrödinger. Before going to this, however, one moral should be drawn from our little fable. When made explicit, the logical inference drawn from London to Nagasaki (or *vice versa*) is *not* drawn directly along the spacelike vector LN (which is physically empty). Each traveller has to remember his flight from Calcutta, the game played there, and hypothesize the flight of the other man from Calcutta. So, truly, the logical inference is drawn along what came to be known as a Feynman [14] zigzag consisting of two timelike vectors, once towards the past, once towards the future. And it is *this* channel that is physically occupied. So, the logic, the mathematics, and the physics all go hand in hand - as it shoud be.

Concluding this introductory Section, the 1927 Einstein,[1] or 1935 E.P.R.[2] paradox, as I see it, is born from the union of two earlier paradoxes. First, the *intrinsic time symmetry* paradox, discussed in the famous Loschmidt [15] and Zermelo [16] papers, the root of which is to be found deeper than in the statistical mechanics: inside the calculus of probabilities *per se*, where there is no intrinsic reason for a dissymetry between a predictive and a retrodictive computation.[8]

The other progenitor of the Einstein paradox is Born's wavelike principle of adding partial (complex) amplitudes rather than probabilities. This is the source of the thousand and one paradoxes of the « new quantum mechanics », which as a rule are verified in (often quite striking) experiments, and thus are truly « Copernican » paradoxes. The Einstein paradox we are discussing is the thousand and oneth, and the special sting in it is due to its spatio-temporal implications.

II. *The mathematics of the Einstein Paradox: Correlated polarizations in cascade experiments*

« Corresponding » to the previous « classical » fable, the travellers will now be (Fig. 3) two « correlated » photons leaving an atomic

[14] R. P. Feynman, « Phys. Rev. », *76*, 749 and 769 (1949).

[15] J. Loschmidt, « Wiener Ber. », *73*, 128 and 136 (1876).

[16] E. Zermelo, « Ann. der Ph. u. Ch. », *57*, 485 (1896).

cascade at C and subsequently detected by two coincidence photomultipliers at L" and N", after they have passed two adjustable linear polarizers at L and N; for commodity those pairs of photons are selected which travel oppositely along an axis x in the laboratory; also, as their frequencies are in fact different, two monochromators L' and N' select the upper and the lower photon of the cascade, each on one semi-axis. This experiment has been performed successfully,[17] and its « paradoxical » answer vindicates quite well the quantum mechanical prediction. There is *absolutely no doubt* that if these beatiful 1972-1976 experiments could have been performed before 1924, in the days of the « old quantum mechanics », they would have produced the same sort of stupefaction as did the 1887 Michelson experiment.

It is fortunate that the mathematics of this remarkable phenomenon can be presented[18] in an elementary form, allowing the non specialist to grasp the point.

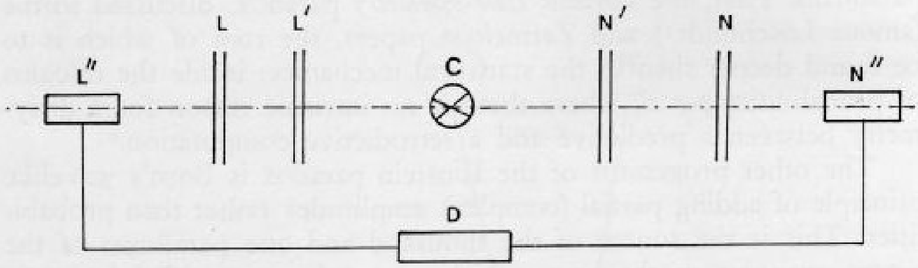

Fig. 3

A photon carried by a plane monochromatic wave impinging normally upon a linear polarizer either passes or is stopped, thus answering respectively *yes* or *no* (denoted as 1 or 0) to the question « is your linear polarization found parallel, or perpendicular, to the direction A of the polarizer? ».

Considering now the pair of photons a and b issuing from the cascade, denoting A and B the directions of the linear polarizers L and N around the axis x (Fig. 3), and setting

$$\alpha \equiv A - B, \quad (1.0)$$

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[17] 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).

[18] O. Costa de Beauregard, « Nuovo Cim. », *42B*, 41 (1977).

we compute, following Born's 1926 rule, the probabilities of the 4 possible answers to the composite question « does the photon a pass the polarizer L and the photon b the polarizer N »? There are two « orthogonal » spinless states of the photon pair which, expressed in terms of circular polarizations, are the « left, left » L_aL_b and the « right, right » R_aR_b helicity states. From these are built the two parity invariant states

$$\frac{1}{\sqrt{2}}(L_aL_b + R_aR_b) = \frac{1}{\sqrt{2}}(Y_aY_b + Z_aZ_b), \tag{1.1}$$

$$\frac{1}{\sqrt{2}}(L_aL_b - R_aR_b) = \frac{i}{\sqrt{2}}[Z_aY_b - Y_aZ_b], \tag{1.2}$$

where the latter expressions are in terms of linear polarizations along two orthogonal axes in the $x = 0$ plane; the transformation formulas are well known and need not be repeated. Each of the above expressions corresponds to a possible type of cascade, and in fact both types have been used in the experiments.[17]

We will now show, following Born's 1926 rule that the probability is the absolute square of the sum of partial amplitudes, that the probabilities of the 4 possible answers are, in the case (1.1),

$$<1,1> = <0,0> = \frac{1}{2}\cos^2\alpha \qquad <1,0> = <0,1> = \frac{1}{2}\sin^2\alpha \tag{1.3}$$

and, in the case (1.2),

$$<1.1> = <0,0> = \frac{1}{2}\sin^2\alpha \qquad <1,0> = <0,1> = \frac{1}{2}\cos^2\alpha. \tag{1.4}$$

The reasoning will be presented in the case (1.1); it would of course be similar in the case (1.2).

Calculation in terms of circular polarizations.

Turning the polarizer L by ΔA will phaseshift the L_aL_b pair by (say) $+\Delta A$ and (then) the R_aR_b pair by $-\Delta A$. Similarly, turning the polarizer N by ΔB will induce the phase shifts $-\Delta B$ and $+\Delta B$. Thus the two amplitudes at stake are $\exp(i\alpha)$ and $\exp(-i\alpha)$, so that, from Born's rule, we deduce formulas (1.3) in the form

$$\begin{aligned} <1,1> = <0,0> &= \frac{1}{8}\,|\exp(i\alpha) + \exp(-i\alpha)|^2 \equiv \frac{1}{4}(1 + \cos 2\alpha) \\ <1,0> = <0,1> &= \frac{1}{8}\,|\exp(i\alpha) - \exp(-i\alpha)|^2 \equiv \frac{1}{4}(1 - \cos 2\alpha). \end{aligned} \tag{1.5}$$

In the latter expressions the diagonal α-independent contribution

$$(1.6) \qquad <1,1>_0 = <0,0>_0 = <1,0>_0 = <0,1>_0 = \frac{1}{4}$$

is the « paleoquantal »[19] prediction, obtained under the assumption that the two photons do leave the cascade C with « hidden » polarizations that they « possess », and *via* the « classical » rule of adding the (two) partial probabilities. The diagonal, interference style, contribution

$$(1.7) \quad \Delta <1,1> = \Delta <0,0> = \frac{1}{4}\cos 2\alpha, \qquad \Delta<1,0> = \Delta <0,1> = -\frac{1}{4}\cos 2\alpha$$

is the « neoquantal correction », and its presence would have caused quite a shock to the paleoquantal physicist. For example, with crossed polarizers, $\alpha = \pi/2$, it entails that $<1,1>_0 = 0$, instead of the (then) expected 1/4!

Calculation in terms of orthogonal linear polarizations.

We know from classical optics that the probability that a photon passes in succession two linear polarizers of relative angle α is $\cos^2\alpha$. Hence the 4 amplitudes at stake in our problem are cosA cosB, sinA sinB, cosA sinB, sinA cosB, whence, according to Born's rule, formulas (1.3) in the form

$$(1.8) \quad \begin{aligned} <1,1> = <0,0> &= \frac{1}{2}(\cos A \cos B + \sin A \sin B)^2 \\ &= \frac{1}{2}(\cos^2 A \cos^2 B + \sin^2 A \sin^2 B) + \frac{1}{4}\sin 2A \sin 2B \\ <1,0> = <0,1> &= \frac{1}{2}(\cos A \sin B - \sin A \cos B)^2 \\ &= \frac{1}{2}(\cos^2 A \sin^2 B + \sin^2 A \cos^2 B) - \frac{1}{4}\sin 2A \sin 2B. \end{aligned}$$

Again, the diagonal contributions (1/2) (...) express the paleoquantal prediction under the assumption that the photons do « possess », when leaving the cascade, hidden linear polarizations along y or z. This expression, however, is not rotationally invariant, so that the paleoquantal physicist would have been led to randomize over all orientations. This is quite easily done by rewriting the neoquantal correction

$$(1.9) \quad \Delta <1,1> = \Delta <0,0> = -\Delta <1,0> = -\Delta <0,1> = \frac{1}{4}\sin 2A \sin 2B$$

[19] Paleo- and neoquantal refer of course to the « old » and the « new » quantum mechanics.

as $(1/2)\cos 2\alpha - (1/2)\cos 2(A+B)$, the mean value of which is $(1/2)\cos 2\alpha$, whence

$$(1.10) \qquad \ll 1,1 \gg_0 = \ll 0,0 \gg_0 = \frac{1}{4} + \frac{1}{8}\cos 2\alpha$$

$$\ll 1,0 \gg_0 = \ll 0,1 \gg_0 = \frac{1}{4} - \frac{1}{8}\cos 2\alpha$$

to be compared with (1.3). Again, the neoquantal value $<1,1> = 0$ obtained with crossed polarizers would have meant quite a shock to the paleoquantal physicist!

Summarizing this section:

1. The experimental results[17] together with their mathematical expression definitely show that *the photons of each pair do not possess « hidden » polarizations when leaving the cascade*. This, of course, is the specification of a general rule of the «new quantum mechanics» - and an extremely direct proof of it.
2. In other words, *the two photons do borrow their (linear) polarizations by interacting with the polarizers, the « paradox » being that they are correlated!*
3. And *how can be tied such a correlation, if not along the only channel that is physically occupied, that is, the Feynman zigzag* LCN (Fig. 2) *connecting* L *and* N *through the source at* C?
4. On the whole, in the (very peculiar) chance game that is played, it is definitely not at C, « when shaken in the cup », but at L and N, « when they stop rolling on the table », that our Alice-in-Wonderland *correlated* quasi-dice are cast.

This *is* the Einstein Paradox!

III. *Other correlation experiments*

As early as 1935 (the year of the EPR article) Furry[20] and Schrödinger[21] suggested that perhaps the paradoxical Einstein correlation would spontaneously disappear when the spatial distance between the two measurements becomes very large. Such a phenomenon is by no means implied in the quantal formalism, and thus must be postulated *ad hoc*. The suggestion has also been put forward that perhaps the

[20] W. H. Furry, « Phys. Rev. », *49*, 393 and 476 (1936).

[21] E. Schrödinger, « Proc. Camb. Phil. Soc. », *31*, 555 (1935).

transition length would be connected with the coherence length of wavetrains. Again, such an assumption is very arbitrary in the case of correlated polarizations, because it is known from astronomy that polarizations are conserved over cosmological distances!

What do we learn, then, from laboratory experiments? Very careful experiments [22] of correlated polarizations of photon pairs issuing from the annihilation of positronium have been performed, where 1º The distance between the measuring devices was immensely larger than the coherence length of wavetrains and 2º The distances between the source C and the measuring devices L and N were arbitrarily and independently varied. No discrepancy with the quantum mechanical prediction was found.

Interpreted in spatio-temporal terms these experiments show that *the formula for the Einstein correlation is invariant with respect to arbitrary displacements of the measuring procedures along the beams followed by the particles* – a very significant conclusion as we shall see.

These beams are of course null-beams in the case of photons, so that (Fig. 2) the LN separation is then necessarily spacelike. However, in the case of heavy particles such as the protons of the Saclay correlation experiment,[23] the LN separation could in principle be rendered timelike. And then, the Einstein correlation would not be less paradoxical than with a spacelike separation, because, instead of a « teleaction », there would occur some sort of a « retroaction » of the later measurement upon the earlier one!

It seems that such an experiment would not be an easy one in the form just said. However, the two-photons experiment could be modified in order to satisfy the timelike separation criterion:[24] one of the two beams could be folded back (Fig. 4) by means of a mirror, and, provided that the straight distance between the two measuring devices L and N is smaller than the difference of the optical lengths between them and the source C, a timelike separation between the two measurements would be achieved.

Finally, the suggestion has been made repeatedly [25] that an experiment where the two polarizers L and N are turned while the photons

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[22] A. R. Wilson, J. Lowe and D. K. Butt, « Journ. Phys. », *G*, 2, 613 (1976); M. Bruno, M. D'Agostino and C. Maroni, « Nuovo Cim. », *40B*, 143 (1977).

[23] M. Lamehi-Rachti and W. Mittig, « Phys. Rev. », *D14*, 2543 (1976).

[24] O. Costa de Beauregard, « Lett. Nuovo Cim. », *25*, 91 (1979).

[25] D. Bohm and Y. Aharonov, « Phys. Rev. », *108*, 1070 (1957).

are flying from C to L and N would be a more crucial experiment than those already performed. This suggestion has generally been made in connection with the Bell[26] theorem problematic, of which I will not say much, because my own problematic is somewhat different. Such an experiment has been defined in a feasible way by Aspect,[27] and the apparatus is in the course of development.

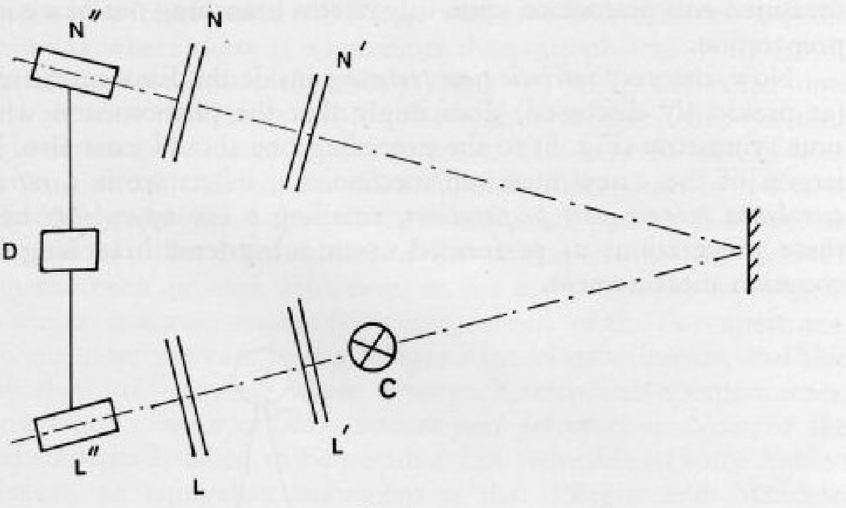

Fig. 4

It is fairly obvious that an experimental proof that the neoquantal correlation formula holds, with the actual orientations of the polarizers as being traversed by the photons, inserted, would be an extremely direct proof of my retroactive causality conception.

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[26] J. S. Bell, « Physics », *1*, 195 (1964). In « Epist. Lett. (Lausanne) », *7*, 2 (1975), Bell has thus summarized his conclusion: λ denoting the set of assumed « hidden variables », l and n two parameters characterizing the adjustable settings of the measuring devices L and N, L and N the corresponding results of the measurements, under the assumption

$$L = L(\lambda, l) \quad N = N(\lambda, n)$$

it is *not*, but under the assumption

$$L = L(\lambda, l, n) \quad N = N(\lambda, l, n)$$

it *is* possible, to reproduce the quantum mechanical prediction.

This is obviously a non-locality statement, and its discussion would be quite similar to the one in Section II of the present paper.

[27] A. Aspect, « Phys. Lett. », *54A*, 117 (1975); « Phys. Rev. », *D 14*, 1944 (1976).

IV. *The time reversed Einstein paradox; Pflegor and Mandel's interference experiments*

As discussed up to know, the Einstein paradox consists in a *predictive correlation between future measurements* entailing, in Einstein-Podolsy-Rosen [2] and d'Espagnat's [28] words, a *non separability* between measurements performed upon subsystems branching out of a common preparation.

Now, the very *intrinsic time symmetry* inside the Einstein correlation (as previously discussed) does imply that the phenomenon which is time symmetric (Fig. 5) to the preceding one should exist also. In the jargon of the « new quantum mechanics », its nature is a *retrodictive correlation between past preparations*, entailing a *non separability* between these preparations as performed upon subsystems branching into a common measurement.

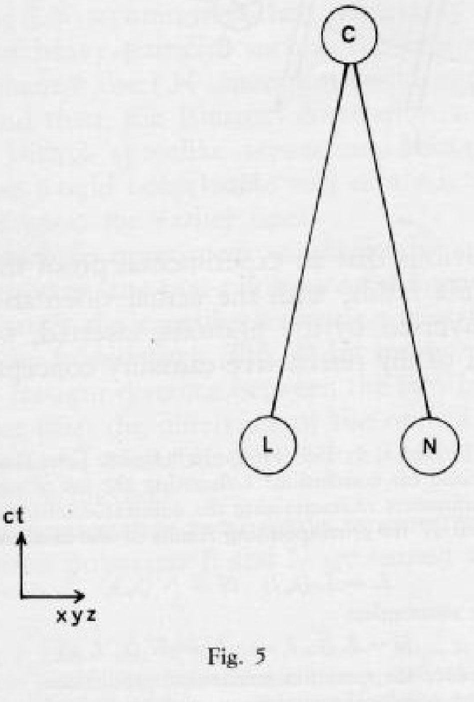

Fig. 5

[28] B. D'ESPAGNAT, *Conceptual Foundations of Quantum Mechanics*, 2nd ed. Benjamin 1976.

Two natural questions then are 1° Has such a phenomenon already been observed? and 2° What of a time reversed correlated polarizations experiment performed along these lines?

The answer to the first question is *yes*. In 1967-1968, Pflegor and Mandel [29] have performed interference experiments using two independent laser sources, which are exactly retrodictive correlation experiments between the occupation numbers at emission. They have shown that the interference still occurs when the intensities are lowered to the point where there is « not more than one photon flying inside the apparatus » or (more rigorously speaking) when the mean time interval between two single photon absorptions is larger than the time of flight from the sources to the detector. The very formalism then shows (and this is well known since the early discussions of the two-slits thought experiment) that, if the interference pattern is observed, one cannot retrodict from which of the two apertures *each* received photon has been emitted. However, in the early thought experiment there was a common source (or cause) ahead of the two apertures. This is no more the case in the Pflegor-Mandel experiments, and this is why they are *essentially* phase coherence retrodictive experiments, demonstrating a *non-separability between past preparations*. Now, if the quantal statistics is taken to be genuine, not reducible to some hidden mechanism, an equivalent statement is that Pflegor and Mandel's results do show that *each* detected photon has been emitted *jointly* by the two lasers working in unison - as if each of them were informed of what the other one is doing, through their future interaction!

This *is* the time reversed Einstein paradox!

V. *Anticascade correlated polarizations experiments*

Things being so, it is only natural to inquire [30] about what lessons can be drawn from an « anticascade » absorption of two correlated linearly polarized photons. Essentially, such an experiment is time symmetric to the one discussed in Section II. Since the advent of the

[29] R. L. Pflegor and L. Mandel, « Phys. Rev. », *159*, 1084 (1967); « Journ. Opt. Soc. Amer. », *58*, 946 (1968).

[30] O. Costa de Beauregard, « Nuovo Cim. », *51B*, 267 (1979).

dye laser it has become routine[31] under the name of « echelon absorption » experiment.

Preliminary remarks are as follows:

If two photons of (well defined) frequencies ν_a and ν_b are to be absorbed jointly so as to lift the energy eigenstate of an atom from W_i to $W_f = W_i + h(\nu_a + \nu_b)$, it is not strictly necessary that the intermediate level $W_i + h\nu_a = W_f - h\nu_b$ be a resonant state. The cross section, however, will be greatly enhanced if it is a resonant state, and only then are the expressions *anti-cascade* or *echelon absorption* appropriate.

Another remark is that the joint absorption occurs only when a definite phase relation exists between the two beams. These beat at the frequency $|\nu_i - \nu_f|$, so that the absorption occurs in pulses.

Thirdly, the intrinsic transition probabilities in emission and absorption are equal – a fact not contradicted by the existence of Einstein's « spontaneous emission probability », as made obvious by replacing in the formula the initial occupation numbers of the final state by the final occupation numbers of this same state.[32]

All this points to the fact that if, say, two linearly polarized independent laser beams are made to interfere, so that the energy eigenstate of detecting atoms is raised from W_i to W_f, and the number of atoms excited per time unit is measured, one shall obtain exactly the same intensity law *versus* the orientations of the polarizers as in the cascade experiments proper.

This is interesting, because the anticascade experiment is *a priori* much easier, faster and more precise than the cascade experiment. No simultaneous counting of the photons is needed, as a simple photometric measurement of the radiation emitted by the excited atoms will suffice to evaluate the number of pairs of photons jointly absorbed per time unit. It even seems that a continuous rotation of the polarizers would be possible, together with a continuous measurement of the reemitted radiation.

As is well known, the simplest, and also the optimal, formula for the polarizations correlation obtains when the angle between the interfering beams is either 0 or π radians. The angle π, commonly

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[31] A. Kastler, « Ann. Phys. » (*Paris*), *6*, 663 (1936); P. F. Liao and G. C. Bjorklund, « Phys. Rev. Lett. », *36*, 584 (1976).

[32] This remark is made by L. de Broglie, *La Mécanique ondulatoire du photon*, t. 2, Paris, Hermann 1942, p. 63.

used with the cascades, is also quite appropriate for the anticascades, as there is no objection to illuminate one laser, L, by the other, N, also as high quality monochromators could be used if necessary [33] (Fig. 6). All the rest is experimental routine, and, by using this approach, a fast and precise [34] check of the theoretical sinusoid would be possible. Thus, a whole set of counter proposals to the quantum theory could be neatly tested.

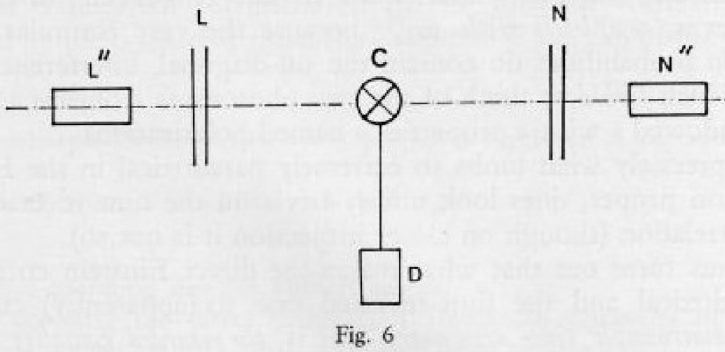

Fig. 6

The rest of this Section will be devoted to a theoretical discussion of aspects of this experiment considered as a thought experiment. The matter discussed will be intrinsic time symmetry *versus* factlike (macroscopic) time asymmetry. It will turn out that some extremely « paradoxical » aspects of the Einstein correlation proper have completely trivial corresponding aspects in the time reversed Einstein correlation.

Two aspects of the Einstein correlation (one that has been [22] and the other one that will be [27] tested experimentally) are felt to be extremely paradoxical: first, that the correlation holds irrespective of the distance between the source and the analyzers (non-locality problem); second, that the significant orientations of the polarizers are those existing while the photons do pass them (retroaction problem). What of the two corresponding problems in the time reversed experiment?

First, one feels *certain* that the beam lengths between the polar-

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[33] A. Kastler, private communication.

[34] One reason among others for more precision with anticascades than with cascades is the quasi-zero aperture of laser beams.

izers L and N (Fig. 6) and the absorbing atoms C are completely irrelevant. In particular, the coherence length of wave trains has nothing to do with this.

Second, one also feels *certain* that the significant orientations of the polarizers at L and N are those existing while the photons do pass them.

In both cases the intuitive feeling is that the two considered photons do « retain » the polarizations which they « acquire » when passing the polarizers, and this sounds quite trivial. This feeling of triviality is, however, *completely misleading*,[35] because the very formulas of the transition probabilities do contain the off-diagonal, interference style, terms, which *forbid* to think of the two photons as « objects » separately « endowed » with « properties » named polarizations ...

So, precisely what looks so extremely paradoxical in the Einstein correlation proper, does look utterly trivial in the time-reversed Einstein correlation (though on closer inspection it is not so).

It thus turns out that what makes the direct Einstein correlation so paradoxical and the time-reversed one so (apparently) trivial is *factlike macroscopic time asymmetry*, that is, *the retarded causality concept*. In other words, *what is paradoxical in the Einstein correlation is intrinsic time symmetry*.

At this point it should be quite clear that the usual, time asymmetric, concept of the wave collapse associated with a measurement (or a preparation) must be wrong, being an inappropriate projection at the elementary level of a macroscopic prejudice. The true, *elementary*, process should be conceived as intrinsically time symmetric, that is, as a *collapse and anticollapse*. To this we will come back.

VI. *S-Matrix formalization of the Einstein correlation*

It should be quite clear by now that the Einstein [1] or EPR [2] paradox is born from the union of *intrinsic time symmetry* with Born's wavelike principle of *adding partial amplitudes rather than probabilities*. And, as both progenitors have a well established paradoxical reputation, what of the offspring!

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[35] F. J. Belinfante, « Amer. Journ. Phys. », *46*, 329 (1978), has an almost identical argument. The apparatus in Fig. 6 is equivalent to the second part of Belinfante's (ideal) apparatus.

Intrinsic time symmetry [36] together with addition of partial amplitudes is also at the very root of the S-matrix formalism, especially in the Feynman [14] presentation of it. Moreover, the previous considerations have dictated the conclusion that the Feynman zigzag is truly the link of the distant Einstein correlation, with the relay in the past for the predictive correlation between future measurements (Fig. 2) or in the future for the retrodictive correlation between past preparations (Fig. 5). It should then be expected that the appropriate, concise, and transparent formalization of the Einstein correlation [30] is provided by the S-matrix formalism – and this is the aim of the present Section.

The ennuple Einstein correlation proper is expressed as an expansion [37]

$$|\Phi\rangle = \sum_j c_j \prod_\lambda |\varphi_{\lambda j}\rangle \tag{6.1}$$

the $|\varphi_\lambda\rangle$'s spanning disjoint Hilbert spaces.

M denoting the direct product of Hermitean operators m acting respectively on the $|\varphi_\lambda\rangle$'s, the « correlated mean value »

$$\langle\Phi|M|\Phi\rangle = \sum_i \sum_j c_i^* c_j \prod_\lambda \langle\varphi_{i\lambda}|m_\lambda|\varphi_{\lambda j}\rangle \tag{6.2}$$

comprizes a sum of diagonal terms

$$\langle\Phi|M|\Phi\rangle_0 = \sum \omega_j \prod_\lambda \langle m_{\lambda j}\rangle \tag{6.3}$$

with by definition

$$\omega_j \equiv c_j^* . c_j \qquad \sum\omega_j = 1, \tag{6.4}$$

$$\langle m_{\lambda j}\rangle \equiv \langle\varphi_{j\lambda}|m_\lambda|\varphi_{\lambda j}\rangle, \tag{6.5}$$

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[36] The Feynman propagator, as used in the S-matrix formalism, is PT-invariant. It thus yields symmetrically an decay, when used in prediction, or an exponential building, when used in retrodiction, fot the higher averaged states.

[37] In the case of only two disjoint Hilbert spaces $|\varphi\rangle$ and $|\psi\rangle$, the expansion of the form $\Sigma c_i |\varphi_i\rangle |\psi_i\rangle$ is known as the « Schmidt canonical expansion », and it is « almost » unique.

The discussion expressed through formulas (6.1) to (6.6) is an extension of the one given by A. Garuccio and F. Selleri, « Nuovo Cim. », *36B*, 176 (1976) and I, « Lett. Nuovo Cim. », *19*, 113 (1977) for the case of only two disjoint Hilbert spaces.

plus a sum of off-diagonal terms

$$(6.6) \qquad \Delta <\Phi \mid M \mid \Phi> = \frac{1}{2} \sum_{i \neq j} c_i^* c_j \prod_{\lambda} <\varphi_{i\lambda} \mid M_\lambda \mid \varphi_{\lambda j}> + \text{c.c.}$$

neither of which is basis invariant.

In this context the distinction between the new, wavelike, probability calculus and the classical one consists in the replacement of formula (6.3) implying partial probabilities by formula (6.1) implying partial amplitudes. If, and only if, the off-diagonal, interference style, contribution (6.6) is rendered zero by using a representation diagonalizing at least one of the m's, is (6.3) a consequence of (6.1) But this is merely the semblance of a mixture, as at is *relative* to the reference frame (the basis).

The expansion (6.1) is a specification of the more general expansion (summation sign omitted)

$$(6.7) \qquad \mid \Phi> = c^{ij \cdots} \mid \varphi_i> \mid \varphi_j> \ldots$$

M denoting the direct product of Hermitean operators m, n, ... acting respectively in the disjoint Hilbert spaces $|\Phi>$, $|\Psi>$, ..., the « correlated mean value »

$$(6.8) \qquad <\Phi \mid M \mid \Phi> = c^{*i'j' \cdots} \cdots c^{ij \cdots} \cdots <\varphi_{i'} \mid m \mid \varphi_j> <\psi_{i'} \mid n \mid \psi_j> \ldots$$

comprizes a fully diagonal contribution where i = i', j = j' ..., namely

$$(6.9) \qquad <\Phi \mid M \mid \Phi>_0 = \omega^{ij \cdots} <m_i> <n_j> \ldots$$

with (no summation this time on repeated indexes)

$$(6.10) \qquad \omega^{ij \cdots} \equiv c^{*ij \cdots} c^{ij \cdots},$$

$$(6.11) \qquad <m_i> \equiv <\varphi_i \mid m \mid \varphi_i>, \quad <n_j> \equiv <\psi_j \mid n \mid \psi_j>, \ldots$$

plus an off-diagonal, interference style, contribution

$$(6.12) \qquad \Delta <\Phi \mid M \mid \Phi> \equiv <\Phi \mid M \mid \Phi> - <\Phi \mid M \mid \Phi>_0$$

Again, the transition from the classical to the wavelike probability calculus consists in the replacement of (6.9) by (6.7). This time, however, the off-diagonal contribution (6.12) is rendered zero if, and only if, the representation diagonalizes *all* the Hermitean operators m, n, ...

So far the reasoning is purely quantal, without any reference to space nor time, and no committment either pro or against relativistic covariance.

From now on we refer explicitely to relativistic quantum mechanics by considering the Schwinger-Feynman-Dyson transition amplitude in the S-matrix formalism. For simplicity we consider the interaction picture proper,[38] with (Fig. 7) initially incoming L_1, M_1, N_1, ... and finally outgoing L_2, M_2, N_2, ... particles in respective states $<\varphi_1|$, $<\psi_1|$, $<\chi_1|$ ... and $|\varphi_2>$, $|\psi_2>$, $|\chi_2>$ ... For example, in quantum electrodynamics, these states will be the photon A's, the electron $\bar{\psi}$'s, and the positron ψ's.

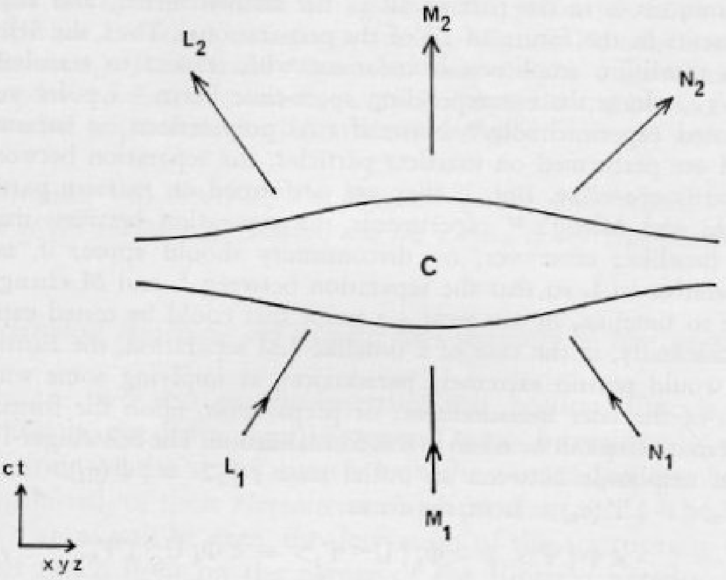

Fig. 7

The point is that, when expressed, for prediction, in terms of the outgoing states, the Schwinger-Feynman transition amplitude is precisely of the general form (6.7). Also, when expressed, for retrodiction, in terms of the incoming states, the Schwinger-Feyman transition amplitude is again of the form (6.7) (with bras instead of kets). Formulas (6.8) to (6.12) then follow. This shows (Fig. 7) that the interaction existing inside the C space-time region does entail the Einstein correlations between the (spatially separated) incoming particles L_1, M_1, N_1, ... on the one hand, and the outgoing particles L_2, M_2, N_2 ... on the other. *So these particles are truly « non separable », and the correlation between them is tied via the Feynman zigzags.*

[38] The interaction picture is chosen because it is the one where the incoming and outgoing particles are thought of as isolated from each other. Of course the computation could be done in the Heisenberg picture, and this would imply another philosophy of non-separability (not discussed in this paper).

This is the relativistically covariant formalization of both a predictive correlation between future measurements L_2, M_2, N_2 ... (as, for example, with the correlated polarizations in cascade experiments [17]) and a retrodictive correlation between past preparations L_1, M_1, N_1, ... (as in the Pflegor-Mandel [29] experiments).

An important remark is that no hypothesis whatsoever is made concerning the space-time regions where the preparations L_1, M_1, N_1 ... and the measurements L_2, M_2, N_2, ... are performed (except of course that any of the preparations is in the past of all of the measurements, and any of the measurements in the future of all of the preparations). Thus, the Schwinger-Feynman transition amplitude is invariant with respect to translating any of the L's ... along the corresponding space-time beam - a point very well substantiated experimentally.[39] Now, if two preparations or measurements L and M are performed on massless particles, the separation between them is necessarily spacelike. But, if they are performed on massive particles, as in Lamehi and Mittig's [23] experiments, the separation between them may well be timelike; moreover, no discontinuity should appear if, say, M is moved relative to L so that the separation between L and M changes from spacelike to timelike, or *vice versa* – a point that could be tested experimentally. Incidentally, in the case of a timelike LM separation, the Einstein correlation would remain extremely paradoxical, as implying some sort of retroaction of the later measurement, or preparation, upon the former one.

One more step can be taken in this formalization. The Schwinger-Feynman transition amplitude between an initial state $|\Phi_1\rangle \equiv |\Phi(\sigma_1)\rangle$ and a final state $|\Psi_2\rangle \equiv |\Psi(\sigma_2)\rangle$ is of the form

$$\langle\Phi|\Psi\rangle \equiv \langle\Phi_1|U^{-1}\Psi_2\rangle = \langle\Phi_1 U^{-1}|\Psi_2\rangle \tag{6.13}$$

with U denoting that specification of the unitary evolution operator U (σ) leading from σ_1 to σ_2. Denoting $|\Theta\rangle\langle\Theta|$ the complete set of orthogonal projectors adapted to a given set of preparations or measurements, one expands (6.13) as (summation sign upon Θ omitted)

$$\langle\Phi|\Psi\rangle \equiv \langle\Phi|\Theta\rangle\langle\Theta|\Psi\rangle. \tag{6.14}$$

In a predictive problem we interpret [40] the $\langle\Theta|\Psi\rangle$'s as the components

[39] This set of remarks constitutes a very strong objection against those feeling that the Einstein correlation is tied directly (rather than indirectly, as in the S-matrix formalism): B. D'Espagnat, « Epist. Lett. (Lausanne », *19*, 19 (1978); N. Cufaro Petroni and J. P. Vigier, « Lett. Nuovo Cim. », in press.

[40] P. A. M. Dirac, *The principles of Quantum Mechanics*, 3rd. ed., Oxford, Clarendon Press 1948, p. 79, and A. Landé, *New Foundations of Quantum Mechanics*, Cambridge University Press 1965, p. 83 interpret an orthogonal complete set of wave functions as transition amplitudes between two different representations.

of the final state (in the Θ representation) and the $<\Phi \mid \Theta>$'s as the coefficients of the expansion. In a retrodictive problem we interpret the $<\Phi \mid \Theta>$s' as the components of the initial state (in the Θ representation) and the $<\Theta \mid \Psi>$'s as the coefficients of the expansion. In both cases the expansion has the general form (6.7).

So, although the Hermitean scalar product $<\Phi \mid \Psi>$ is symmetric in the initial and the final states, it can be thought of, and used, asymmetrically, either as the projection of $\mid \Phi>$ upon $\mid \Psi>$ (called *collapse* for prediction *via* retarded waves with sources on σ_2) or as the projection of $\mid \Psi>$ upon $\Phi>$ (which can be called *anticollapse*, for retrodiction *via* advanced waves with sinks on σ_1). Fock [41] and Watanabe [42] are among those [43] who have clearly emphasized that, in quantum mechanics, retarded and advanced waves should be used respectively for (blind) statistical prediction and retrodiction.

Concluding this Section, *the Feynman zigzag truly is the « deus ex machina » of the Einstein correlation, and the wizard of the Einstein paradox.*

VII. *Relativistic covariance and intrinsic time symmetry in first quantization*

There are two reasons for inserting this Section. One is that a missing link in the Schwinger-Feynman-Dyson formalism is a covariant definition of the states upon which the occupation numbers are to be distributed, of their Hermitean scalar product, etc ... The second reason is that, as will be seen, the derivation of the appropriate formalism sheds much light on the nature of the Einstein paradox.

We [44] consider for simplicity the case of incoming and outgoing free particles,[45] which obey the (unspecified spin) Klein-Gordon equation, and a specified spin equation (Dirac, Petiau-Duffin-Kemmer, etc ...). To each spinning particle equation is associated a projector P, projecting any solution of the Klein-Gordon equation as a solution of the spinning particle equation.

The Fourier expansion of any solution of the wave equation shall be

[41] V. Fock, « Dokl. Akad. Nauk SSSR », *60*, 1157 (1948).

[42] S. Watanabe, « Rev. Mod. Phys. », *27*, 179 (1955).

[43] O. Costa de Beauregard, « Cah. de Phys. », *12*, 317 (1958); Y. Aharonov, P. G. Bergmann and J. L. Lebowitz, « Phys. Rev. », *134B*, 1410 (1964); F. J. Belinfante, *Measurements and Time Reversal in Objective Quantum Theory*, Pergamon Press 1975.

[44] O. Costa de Beauregard, *Précis de Mécanique Quantique Relativiste*, Paris, Dunod 1967.

[45] This is not a necessary restriction.

expressed as an integral over the mass shell [46] – over *both sheets* of it, otherwise, as will be seen, the formalism would not work. The case of massless particles can be treated either by starting from a Fourier expansion over the light cone, or else by conferring an arbitrarily small rest mass k to our particles, as will be done here.

Then comes the question of the reciprocal Fourier transform [47] and of the Parseval equality, that is, of the expression of the Hermitean scalar product in its space-time x and its 4-frequency k representations. The guess is that, in x-space, the integral should be an invariant one over an arbitrary spacelike surface σ, and a conservative one by virtue of the wave equation. Thus, denoting $\bar{\psi}[\partial_\lambda]\psi$ and $\bar{\psi}\,\alpha_\lambda\,\psi$ the well-known Gordon and Dirac-style 4-currents ($\lambda = 1, 2, 3, 4$; $x^4 = it$; $c = 1$, $h/2\pi = 1$; $\partial_\lambda = \overrightarrow{\partial}_\lambda - \overleftarrow{\partial}_\lambda$) it can be shown [44] – and is almost obvious – that the expressions of the Hermitean scalar product in association with the (second order) Klein-Gordon equation are

$$(7.1) \qquad <a\,||\,b> \;= -\frac{i}{2k}\iiint_\sigma \bar{\psi}_a\,[\partial_\lambda]\,\psi_b\,d\sigma^\lambda = \frac{1}{k}\iiint_\eta \bar{\theta}_a k_\lambda\,\theta_b\,\varepsilon(k)\,d\eta^\lambda$$

and in association with the (first order) spinning particle equation

$$(7.2) \qquad <a\,|\,b> \;= i\iiint_\sigma \bar{\psi}_a\,\alpha_\lambda\,\psi_b\,d\sigma^\lambda = i\iiint_\eta \bar{\theta}_a\,\alpha_\lambda\,\theta_b\,\varepsilon(k)\,d\eta^\lambda.$$

As previously said, the η integral is over both sheets of the mass shell

$$(7.3) \qquad \eta(k) \equiv k_\lambda\,k^\lambda + k^2 = 0$$

with $\eta(k) = +1$ on the positive and -1 on the negative frequency shell; $d\eta^\lambda$, which is such that

$$(7.4) \qquad k^\lambda\,d\eta = -\,k d\eta^\lambda,$$

and $d\sigma^\lambda$, are the 4 vectors representing the 3-fold volume elements on η and σ respectively; the α_λ's are of course the spin matrices ($\alpha_\lambda = \gamma_\lambda$ in the Dirac case, $= \beta_\lambda$ in the Petiau-Duffin-Kemmer case, etc. ...). Due to the Gordon decomposition formula for the 4-current, the expressions

$$(7.5) \qquad <a\,||\,b> \;=\; <a\,|\,b>$$

are integrally equal in the x representation.

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[46] M. Riesz, *Actes du 10e Congrès des Mathématiciens Scandinaves*, Copenhague 1966, p. 123.

[47] O. Costa de Beauregard, « Journ. Phys. » (Paris) *16*, 770 (1955) and *17*, 872 (1956).

In the k representation they are even locally equal, as seen by using the consequences

$$(7.6)\qquad k^{\lambda}\,\bar{\theta}_a\,\alpha_{\lambda}\,\theta_b = -\,ik\,\bar{\theta}_a\,\theta_b,$$

$$(7.7)\qquad k^{\lambda}\,\bar{\theta}_a\,\theta_b = ik\,\bar{\theta}_a\,\alpha^{\lambda}\,\theta_b,$$

of the spinning particle equation, together with (7.3) and 7.4).

Using the well-known Dirac notation, we rewrite (7.1) and (7.2) as

$$(7.8)\qquad \langle a\,||\,b\rangle = \langle a\,||\,x\rangle\ \langle x\,||\,b\rangle = \langle a\,||\,k\rangle\ \langle k\,||\,b\rangle,$$

$$(7.9)\qquad \langle a\,|\,b\rangle = \langle a\,|\,x\rangle\ \langle x\,|\,b\rangle = \langle a\,|\,k\rangle\ \langle k\,|\,b\rangle.$$

Orthonormality is, as usual, expressed as

$$(7.10)\qquad \langle a\,||\,b\rangle = \langle a\,|\,b\rangle = \delta_{ab}$$

Introducing the Fourier nucleus

$$(7.11)\qquad \langle x\,||\,k\rangle = \langle k\,||\,x\rangle^{*} = \begin{cases} (2\pi)^{-3/2}\exp(ik_{\lambda}x_{\lambda}) & \text{if } \eta(k) = 0 \\ 0 & \text{otherwise} \end{cases}$$

$$(7.12)\qquad \langle x\,|\,k\rangle = P\,\langle x\,||\,k\rangle$$

we write the reciprocal Fourier transforms as

$$(7.13)\qquad \langle x\,||\,a\rangle = \langle x\,||\,k\rangle\ \langle k\,||\,a\rangle,\quad \langle k\,||\,a\rangle = \langle k\,||\,x\rangle\ \langle x\,||\,a\rangle;$$

$$(7.14)\qquad \langle x\,|\,a\rangle = \langle x\,|\,k\rangle\ \langle k\,|\,a\rangle,\quad \langle k\,|\,a\rangle = \langle k\,|\,x\rangle\ \langle x\,|\,a\rangle.$$

By substituting the second formula (7.13) into the first one and setting

$$(7.15)\qquad \langle x'\,||\,x''\rangle = \langle x'\,||\,k < \ \rangle\ \langle k\,||\,x''\rangle = \langle x'\,||\,x\rangle\ \langle x\,||\,x''\rangle$$

we solve the Cauchy problem [48] in the form

$$(7.16)\qquad \langle x'\,||\,a\rangle = \langle x'\,||\,x\rangle\ \langle x\,||\,a\rangle$$

where, according to the (first form of) the definition (7.15), $\langle x'\,||\,x\rangle$ is noneelse than the well-known Jordan-Pauli propagator, which is odd in $x' - x''$ and, thus, zero outside the light cone. It was of course imperative to end up with formula (7.16) and the Jordan-Pauli propagator inside it;

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[48] See J. Schwinger, « Phys. Rev. », *74*, 1439 (1948). See p. 1451.

this is why one *had* to have both the positive and the negative frequencies inside formulas (7.13) and (7.14). The Jordan-Pauli propagator is remarkable in that it is the only propagator expressible as a linear combination of either the D_+ and D_- contributions of the η_+ and η_- sheets of η, and of the retarded D_r and advanced D_a propagators:

$$(7.17) \qquad <x' || x''> \equiv D(x' - x'') = D_+ - D_- = D_r + D_a.$$

This equality implies a (partial) binding between two intrinsic symmetries: that between particles and antiparticles (using the well-known Dirac and Feynman interpretation) *and that between retarded and advanced waves.* Some implications of this will be expressed later.

Formula (7.16), with $x' - x''$ spacelike, can also be considered as the expansion of the wavefunction $<x' || a>$ at any point-instant x' upon the complete orthogonal set of Jordan-Pauli propagators $<x' || x>$ with apexes x on σ, the coefficients of the expansion being the values $<x || a>$ of $<x' || a>$ on σ; orthogonality of these propagators is expressed in the latter expression (7.15), as $<x' || x''>$ is 0 outside the light cone.

Finally, as expressions (7.11) and (7.15) are Fourier associated, we deduce, by transposing a well-known Schrödinger argument, that the position operator is x^λ *modulo that* x^λ *ends on* σ (that is, only 3 degrees of freedom; for example, the components of x). [40]

I mention *en passant* the formula

$$(7.18) \quad <k' || k''> = <k' || x> <x || k'' = <k' || k> <k || k''>$$

expressing orthogonality of two Fourier nucleuses in k space , provided that k' and k'' (ending on η) are different.

Formulas similar to (7.15), (7.16) and (7.17) with one vertical bar instead of two can, of course, be derived from the (7.14)'s. Incidentally,

$$(7.19) \qquad <x' | x''> \equiv P <x' || x''>.$$

VIII *The covariant position (or position plus polarization) measurement*

The covariant extension (Fig. 8) of the question « Do we find at time t the Schrödinger particle inside the volume element dx dy dz? » clearly is « Do we find at σ the relativistic particle crossing a given

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[40] A difference exists between this definition of the covariant position operator implying positive and negative frequencies, and the well-known Newton and Wigner one implying only positive frequencies (R. F. O'Connell, private communication).

element $d\sigma^\lambda$ of σ? » The eigenfunction corresponding to the Dirac $\delta(x' - x)$ thus is the Jordan-Pauli propagator $D(x' - x) \equiv \langle x' | | x \rangle$. Correspondingly, the probability distribution for finding the particle « at x^λ at pseudo time σ » is the Gordon current $\langle a | | x \rangle \langle x | | a \rangle$.

All this means that finding the particle « at x^λ at σ » implies that it has come inside the past, and will go inside the future, light cone - which, of course, is known since Minkowski *except for one important point.*

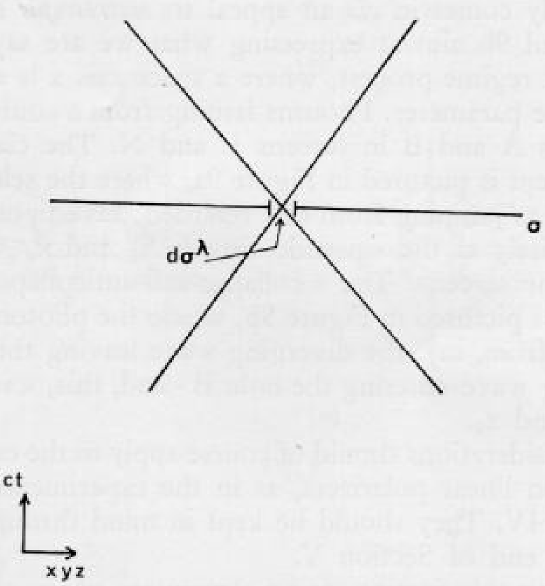

Fig. 8

The position measurement performed at pseudo time σ does collapse the wave function $\langle x | | a \rangle$ into $\langle x' | | x'' \rangle$ and, as $\langle x' | | x'' \rangle$ is odd in $x' - x''$, *this collapse affects symmetrically both past and future.* In the terminology of Section VI, it is together a « collapse and anticollapse ».

This is *precisely* the key I am proposing for formalizing the Einstein paradox: *Two distant position measurements with spacelike separation* (or, in the single bar formalism, two distant position plus polarization measurements) *do produce the same collapse in their common past.* Similarly, *two distant preparations with spacelike separation do produce the same anticollapse in their common future*, which formalizes the time-reversed Einstein paradox.

We are thus led to deny categorically the generally accepted [50] concept of a time asymmetric « wave collapse », and to replace it by the time symmetric « collapse and anticollapse » concept exemplified in Figure 8. This, of course, is consistent with the idea that time symmetry is a trait that is *essential* at the elementary level, and that time asymmetry is factlike, and appears only at the macroscopic level.[51] P.C.W. Davies [52] is another author emphasizing strongly that time asymmetry in the quantum measurement process is of macroscopic origin, and only comes in *via* an appeal to *macroscopic statistics*.

Figs. 9a and 9b aim at expressing what we are saying in terms of a permanent regime process, where a space axis x is a valid substitute for the time parameter. Photons issuing from a source S successively pass holes A and B in screens L and N. The classical « wave collapse » concept is pictured in Figure 9a, where the selected photons are thought of as jumping from one retarded wave upon another one and, this, precisely at the « pseudo times » x_L and x_M which are the abscissa's of the screens. The « collapse-and-anticollapse » concept I am proposing is pictured in Figure 9b, where the photons are thought of as jumping from, say, the diverging wave leaving the hole A unto the converging wave entering the hole B - and, this, « somewhere in-between » x_L and x_M.

Similar considerations should of course apply to the case of photons impinging upon linear polarizers, as in the experiments discussed in Sections II and IV. They should be kept in mind throughout the discussion at the end of Section V.

Summarizing this Section, as an elementary process, the « quantal transition », or « wave collapse », cannot be else than time symmetric. It is a « collapse-and-anticollapse », as pictured in Figure 8 and Figure 9b, and expressed in the mathematics of formula (7.16). Time asymmetry creeps in only as factlike, and of macroscopic origin, *via* an assumed repetition of the process.

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[50] See for example H. D. Zeh, « Found. Phys. », 9, 803 (1979).

[51] For a general presentation and a guide to the (extensive) literature see O. Costa de Beauregard, « Studium Generale », *24*, 10 (1971) or « Synthese », *35*, 129 (1977).

[52] P. C. W. Davies, *The Physics of Time Asymmetry*, Surrey University Press 1974. See p. 167.

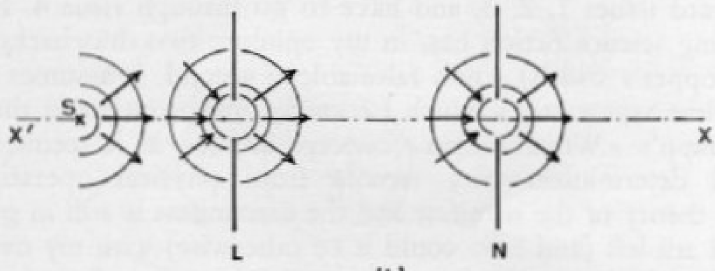

Fig. 9

IX. *Physical conclusion*

In a recent paper devoted to Bell's theorem Eberhard [53] concludes that the overall experimental verifications of the reality of the Einstein paradox allow four, and only four issues.

1. « Do not think, just compute, and thus avoid headaches ». This is playing the ostrich (and the majority's vote).

2. It may be that quantum mechanics is only an approximation, that under sophisticated conditions the paradoxical Einstein correlation fails, and that locality can be saved after all. Numerous papers have been,[20-21] and still are [54] exploring this (ever narrowing) possibility.

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[53] P. Eberhard, « Nuovo Cim. », *46B*, 392 (1978).

[54] F. Selleri, « Found. Phys. », *8*, 103 (1978); L. Schiavulli and F. Selleri (preprint).

3. If not quantum mechanics, it is special relativity which may turn out to be wrong. Specifically, the collapse of the state vector looks like a non-local phenomenon implying some sort of telegraphing outside the light cone.[55]

4. If the general schemes of neither quantum mechanics nor special relativity can be shaken – and, after all, neither of them has ever been found faulty [56] – then *the only issue left is changing the accepted, macroscopic, causality concept*. In this respect Eberhard cites three proposals: Everett's,[57] Stapp's,[11] and mine;[9] he could perhaps have added the Bohm and coworkers' one.[58]

As implied in my above presentation of Eberhard's conclusions, I disregard issues 1, 2, 3, and have to go through issue 4. Everett's fascinating science fiction has, in my opinion, two drawbacks: first it is (in Popper's words) « non falsifiable »; second, it assumes an « intrinsic time asymmetry » which I consider inappropriate at the micro-level. Stapp's « Whiteheadian » concept implies, as it seems, a metaphysical determinism very remote from physical operationalism. Bohm's theory of the manifest and the unmanifest is still in gestation.

So I am left (and how could it be otherwise) with my own interpretation, which consists in *a quite straightforward reading of relativistic quantum mechanics as it exists, either in first or second quantization*.

Non-locality is definitely implied in this scheme, and it consists in spacelike connections established via Feynman zigzags. While telegraphing directly outside the light cone remains strictly forbidden, indirect telegraphing is allowed, because Einstein's prohibition to telegraph into the past is considered as factlike, and present only at the macrolevel, and removed at the micro-level. Figure 10 gives a humoristic presentation of the conception I am proposing.

The taboo I am thus trespassing is « No reaction of the observation upon the observed system », and a few remarks are in order at this point. One is that it has often been written that such a trespassing is linked with the non-zero value of Planck's constant h, and is thus

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[55] B. D'Espagnat, *Conceptual Foundations of Quantum Mechanics*, 2nd ed. Benjamin 1976. See pp. 90, 95, 238, 265, 281. C. Piron, « Epist. Lett. (Lausanne) », *19*, 1 (1978).

[56] There still are unsolved (and important) problems in both the basic quantum and relativistic schemes. But this is *very* different from finding them faulty!

[57] H. Everett, « Rev. Mod. Phys. », *29*, 454 (1957).

[58] D. Bohm and co-workers, various preprints.

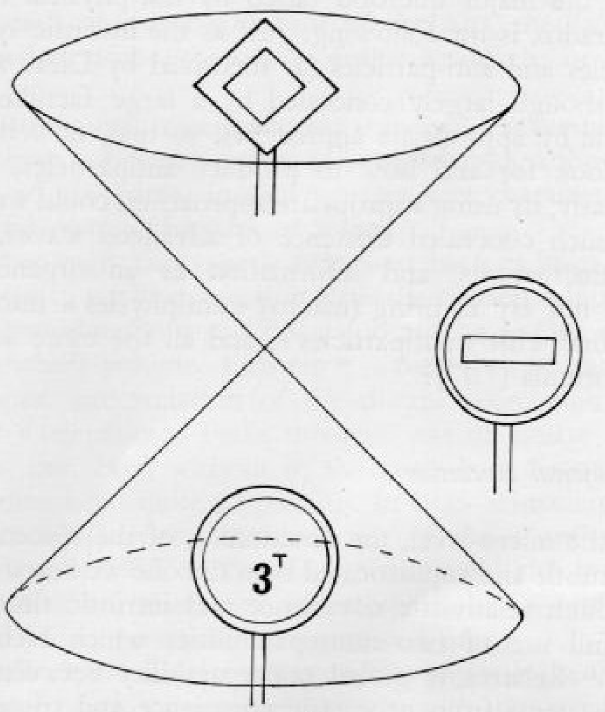

Fig. 10

typical of an appropriate interpretation of quantum mechanics. In my opinion this trespassing is already implied in the non-zero value of Boltzmann's constant k together with the equivalence formula

$$N = k \, \mathrm{Ln} \, 2 \, I \tag{9.1}$$

between negentropy N and information I, and with the intrinsic symmetry between information as gain in knowledge ($N \rightarrow I$ at the reception of a message) and as organizing power ($I \rightarrow N$ at the emission of the message). This intrinsic symmetry is of course tied with the intrinsic time symmetry of the probability calculus.[51]

What comes in with the finiteness of Planck's constant is de Broglie's wave mechanics, Born's wavelike probability calculus, and Fock[41] and Watanabe's[42] symmetry of statistical prediction *via* retarded waves and statistical retrodiction *via* advanced waves.

Finally, the major question raised by the physical reality of the Einstein paradox is the following. Just as the intrinsic symmetry between particles and anti-particles (as theorized by Dirac and by Feynman) can, though largely concealed by a large factlike asymmetry, be overcome by appropriate approaches, so that, now that we know where to look for and how to produce antiparticles, we do have them; similarly, by using appropriate approaches, could we not uncover the very much concealed existence of advanced waves, progressing statistical fluctuations, and information as an organizing power? Should we not try to bring (macro) « antiphysics » into the open as we have done with « antiparticles », and all the more so that we do have the formula (7.17)?

X. *Metaphysical conclusion*

So, at the micro-level, the functioning of the spacetime telegraph is *far more* subtle and sophisticated than the one we know at the macro-level. Through relativistic covariance and intrinsic time symmetry [59] it makes full use of two nonseparabilities which blend quite well together: 1° Relativistic global nonseparability between past and future, which stems from geometric covariance and trissection of spacetime into past, future and elsewhere (Fig. 10) instead of the previously accepted dissection into past and future; 2° Quantal nonseparability, as discussed at length in this paper.

I know of two metaphysical doctrines which seem to fit well with the present physical situation.

In Bergson one reads *passim* that there is no such being as a Homo Sapiens, because in fact there is a Homo Faber who, in his crude pragmatic approach, arbitrarily cuts through reality and, thus, severs parts which should not be severed. If he were able to approach things through Intuition, he would see them in a new, and much more revealing, light. Among other things, he would hold the key to « Creative Evolution ».

The Vedantas are even more explicit. They state *passim* that *separability* is an *illusion*, which is *relative* to the ordinary pragmatic ap-

[59] The intrinsic time symmetry we are speaking of is the one between retarded and advanced waves, blind prediction and retrodiction. My forthcomming paper (« Found. Phys. », in press) entitled *CPT-Invariance and Interpretation of Quantum Mechanics* presents CPT-invariance as the covariant and physical generalization of the classical T-symmetry.

proach. If, through appropriate meditation techniques, one gains *cosmic consciousness*, this is cognizance of the *past*, the *future* and the *elsewhere*, together with possession of the « siddis », or paranormal powers.

The quantum measurement process *is* indeed a severance by which the overall phase coherence is lost to the observer, although it does still pervade *all* spacetime, in the *covariant* way characteristic of the (relativistic and quantal) physics of waves.

Curiously enough, this exactly brings us back to what the Founding Fathers had to say in connection with the nonseparability paradox. In his long Introduction and Conclusion to the Essays collected in his 1949 *Festschrift* volume, Einstein [60] writes that he cannot accept the Copenhagen interpretation of the distant correlation because it would imply « telepathy ». Bell's theorem was of course not known in these days, but, even without it, the analysis in Section II above would have then been quite perplexing. In 1935 Schrödinger [61] wrote similarly that the Copenhagen rendering of the correlation would imply « magic ». In 1957 de Broglie [62] wrote (and this was after my discussions with him) that such an interpretation would contradict « our classical views pertaining to space and time ».

The overall view I am defending in this paper *is* the Copenhagen interpretation of *relativistic quantum mechanics* with, however, *one change*. Information is taken as not only a gain in knowledge but *also*, and *together*, as an organizing power. *This shows up in the very formalism* (see Section VII) and implies, at the elementary level, the *symmetric presence of retarded and advanced waves.*

This implies also a *reaction of the observer upon the observed system*, which *should be observable* in the form of what parapsychologists call *psychokinesis*.[63] Although he does not use the later word, E. P. Wigner,[64] using arguments analogous to mine, has already expressed a similar conclusion.

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[60] A. Einstein in *Einstein Philosopher Scientist*, P. A. Schilpp ed., The Library of Living Philosophers, Evanston, Ill. 1949, p. 85 and 683.

[61] E. Schrödinger, « Naturwiss. », *48*, 844 (1935). See p. 845.

[62] L. de Broglie, *Une Tentative d'Interprétations Causale ... de la Mécanique Ondulatoire*, Paris, Gauthier Villars 1957, p. 73.

[63] H. Schmidt, 1977, *Proc. Intern. Conf. Cybernetics and Society* (I.E.E.E.) p. 535 and « Bull. Amer. Phys. Soc. », *24*, 38 (1979), has publicly defended psychokinesis before the physics community.

[64] E. P. Wigner, *Symmetries and Reflexions*, MIT Press 1967, pp. 171-184.

This should also show up in quantal correlation experiments such as the one by Shimony and co-workers,[65] which was found inconclusive *for one very obvious reason: at least one of the two observers should have been a «psychic»*! This also amounts to say that, contrary to an often expressed opinion, the Einstein correlation *could* be used as a spacelike telegraph – *provided that at least one of the two correspondents is a psychic.*

But of course this amounts to say that dis-covering advanced waves means un-covering anti-physics, and, thus, the full implications of relativistic and quantal unseparability.

RIASSUNTO

La correlazione a distanza di Einstein si presenta sia quale correlazione previsionale (*predictive correlation*) tra misurazioni future sia quale correlazione a ritroso (*retrodictive correlation*) tra preparazioni passate. Il primo fenomeno è provato da diversi esperimenti di polarizzazione mentre il secondo è illustrato dagli esperimenti di interferenza tra due fasci laser eseguiti da Pflegor e Mandel.

I due fenomeni sono qui trattati sinteticamente mediante il formalismo della matrice S di Schwinger-Feynman verificando che essi si inquadrano nello schema della meccanica quantistica relativistica.

Si mostra così che il cosiddetto paradosso di Einstein discende dal connubio di due paradossi anteriori: 1) *il principio della simmetria intrinseca del tempo*, già discusso nella meccanica statistica classica da Loschmidt e da Zermelo; 2) *il principio di Born dell'addizione delle ampiezze parziali* (in luogo delle probabilità) il quale vieta di attribuire alle entità elementari proprietà individuali separate.

Lo zigzag di Feynman appare quindi come il *deus ex machina* della correlazione di Einstein e l'esorcista del paradosso di Einstein. Il concetto di causalità macroscopica ritardata risulta rimpiazzato, a livello elementare, dal *concetto di causalità cronosimmetrica*.

Le relative conseguenze filosofiche vengono poi brevemente discusse.

[65] J. Hall, C. Kim, B. Mc. Elroy and A. Shimony, «Found. Phys.», *7*, 759 (1977).