WHY DOES NONLOCALITY SUPPORT BOHM's THEORY?

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QUANTUM MECHANICS

PHYSICAL SYSTEM

$\longrightarrow$ STATE

ALGORITHM

$\longrightarrow$ COMPUTE

PROBABILITIES of 'MEASUREMENTS'

PROBABILITIES of WHAT EXACTLY ?

QUANTUM ALGORITHM

Ψ STATE $\Psi_0 \longrightarrow \Psi_t = U(t)\Psi_0$

A "OBSERVABLE" = OPERATOR

$A\Psi_i = \lambda_i \Psi_i$

$\Psi = \sum_i c_i \Psi_i \qquad \sum_i |c_i|^2 = 1$

PROBA (Result = λ_i when measure A ; If state = Ψ) = $|c_i|^2$

AFTER THAT, THE STATE JUMPS OR IS REDUCED OR COLLAPSES TO Ψ_i

PROBABILITY of WHAT ?

(at least) 2 Meanings for this probability

1. Orthodox, standard

$\longrightarrow$ Our most fundamental physical theories deal only with those macroscopic regularities called measurements.

2. Implicit

$\longrightarrow$ Properly designed experiments reveal *preexisting* (but unknown) properties of the system.

“ It would seem that the theory is exclusively concerned about “results of measurement”, and has nothing to say about anything else. What exactly qualifies some physical systems to play the role of “measurer”? Was the wavefunction of the world waiting to jump for thousands of millions of years until a single-celled living creature appeared? Or did it have to wait a little longer, for some better qualified system. . . with a Ph D? ”

J. BELL

“ The problem of measurement and the observer is the problem of where the measurement begins and ends, and where the observer begins and ends. Consider my spectacles, for example : if I take them off now, how far away must I put them before they are part of the object rather than part of the observer ? There are problems like this all the way from the retina through the optic nerve to the brain and so on. I think, that – when you analyse this language that the physicists have fallen into, that physics is about the results of observations – you find that on analysis it evaporates, and nothing very clear is being said ”

J.S. BELL

We can no longer speak of the behavior of the particle independently of the process of observation. As a final consequence, the natural laws formulated mathematically in quantum theory no longer deal with the elementary particles themselves but with our knowledge of them. Nor is it any longer possible to ask whether or not these particles exist in space and time objectively...

W. HEISENBERG

“ I am, in fact, firmly convinced that the essentially statistical character of contemporary quantum theory is solely to be ascribed to the fact that this (theory) operates with an incomplete description of physical systems. . .

[In] a complete physical description, the statistical quantum theory would. . . take an approximately analogous position to the statistical mechanics within the framework of classical mechanics ”

A. EINSTEIN

NO HIDDEN VARIABLE THEOREM: PROBLEM FOR THE IMPLICIT VIEW.

$\nexists$ MAP $v : \mathcal{A} \to \mathbb{R}$

$\downarrow$

set of matrices

such that $\forall\ A, B \in \mathcal{A}$

1) $v(A) \in$ {eigenvalues of A}

2) If $[A, B] = 0$, then

$$v(AB) = v(A)v(B)$$

$\Rightarrow$ CONTEXTUALITY

NO USE OF QUANTUM FORMALISM

$v(A) =$ preexisting, but unknown value of A.

BOHMIAN MECHANICS

STATE (Ψ, Q)

1. SCHRÖDINGER'S EQUATION

$$\Psi_0 \to \Psi_t = U(t)\Psi_0$$

$$i\hbar\partial_t\Psi = H\Psi$$

2. GUIDING EQUATION

$$\dot{Q}_k = \frac{\hbar}{m_K} \quad \frac{\mathrm{Im}(\Psi^*\nabla_k\Psi)}{\Psi^*\Psi}(Q_1, \ldots, Q_N)$$

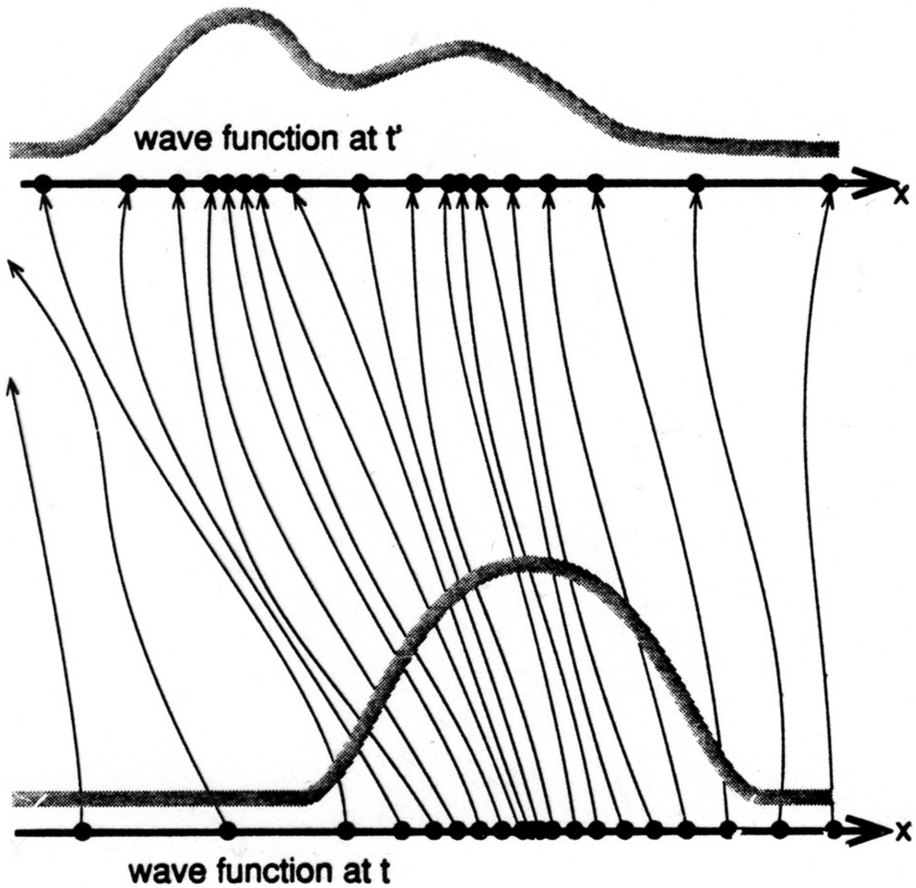
$$= V_\Psi^k(Q)$$

3. EQUIVARIANCE

$$|\rho_0| = |\Psi_0|^2 \to \rho_t = |\Psi_t|^2$$

WHERE Ψ_t comes from 1

ρ_t comes from 2


wave function at t'
x
x
wave function at t

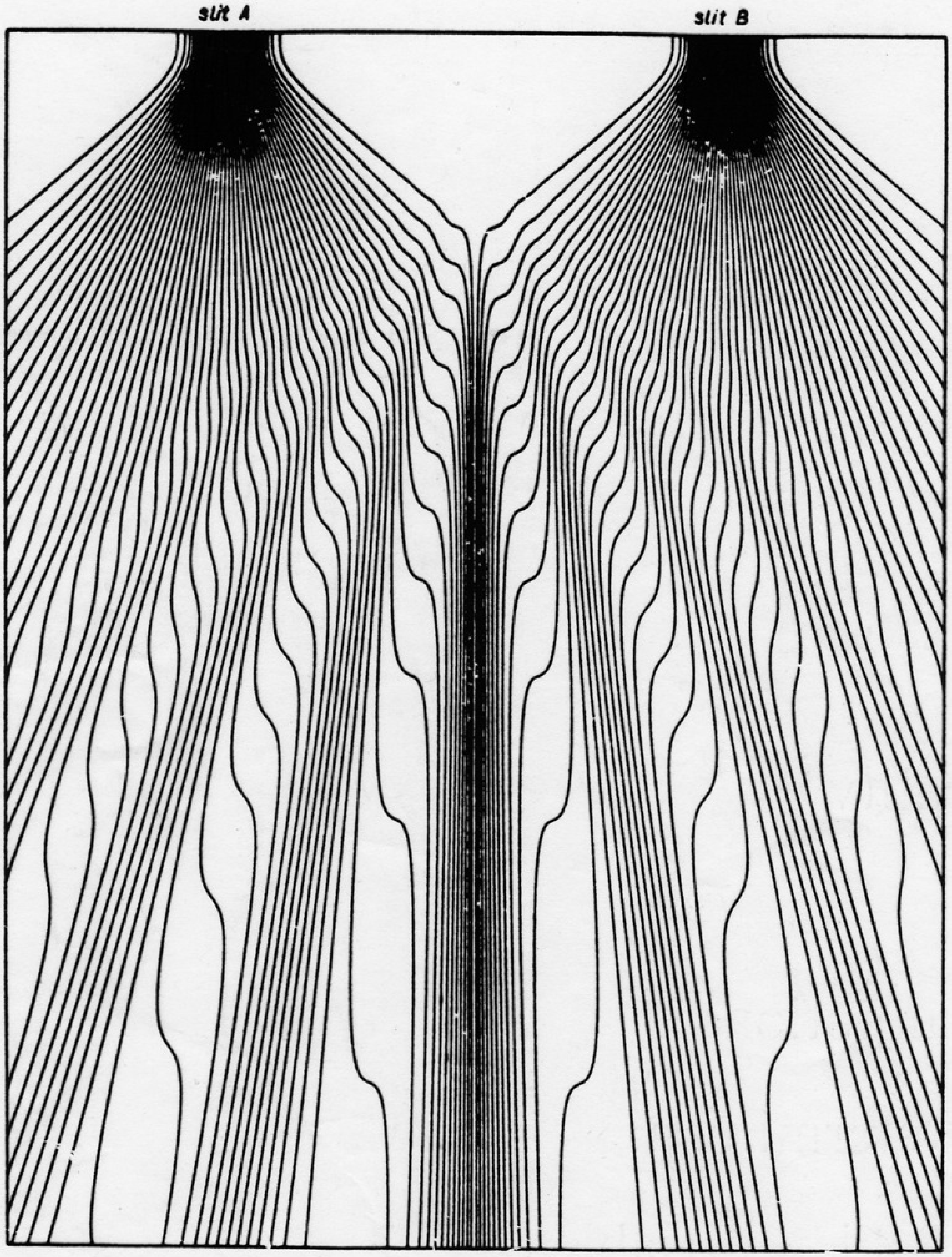


Figure 9.3 Trajectories for two Gaussian slits with a Gaussian distribution of initial positions at the slits.

“ It is not clear from the smallness of the scintillation on the screen that we have to do with a particle? And is it not clear, from the diffraction and interference patterns, that the motion of the particle is directed by a wave? De Broglie showed in detail how the motion of a particle, passing through just one of two holes in screen, could be influenced by waves propagating through both holes. And so influenced that the particle does not go where the waves cancel out, but is attracted to where they cooperate. This idea seems to me so natural and simple, to resolve the wave-particle dilemma in such a clear and ordinary way, that it is a great mystery to me that it was so generally ignored ”

J. BELL

QUALITIES

1. (Double) meaning of Ψ

   a) Dynamical

   $\dot{Q} = V_\Psi(Q)$

   b) Statistical

   $\rho = |\Psi|^2$

$$\mathrm{H}_{\mathrm{class}} \quad \sim \quad \log \Psi$$

$$\swarrow \quad \searrow$$

Generates Dynamics $\qquad e^{-\beta H}$ in EQUILIBRIUM

2. Explains No Hidden Variables

   or CONTEXTUALITY

      EX : SPIN

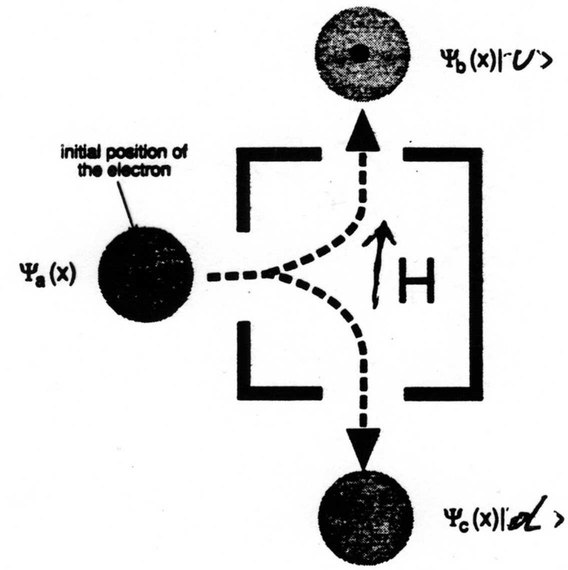


Figure 7.8

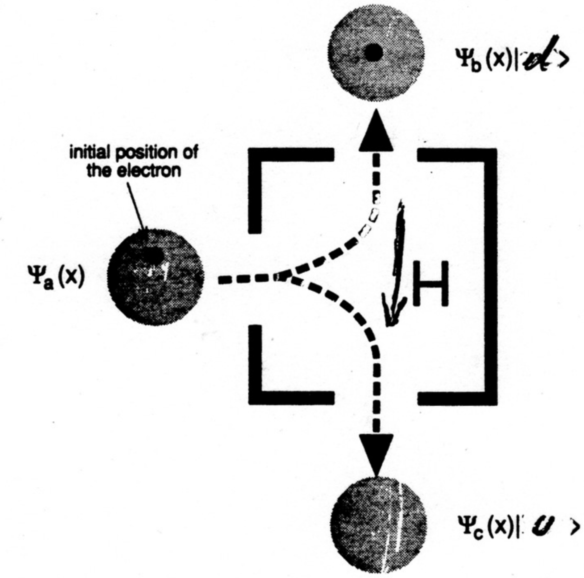


Figure 7.8

“ It is therefore not, as is often assumed, a question of a re-interpretation of quantum mechanics-the present system of quantum mechanics would have to be objectively false, in order that another description of the elementary processes that the statistical one be possible ”

J. VON NEUMANN

“ No concealed parameters can be introduced with the help of which the indeterministic description could be transformed into a deterministic one. Hence, if a future theory should be deterministic, it cannot be a modification of the present one but must be essentially different ”

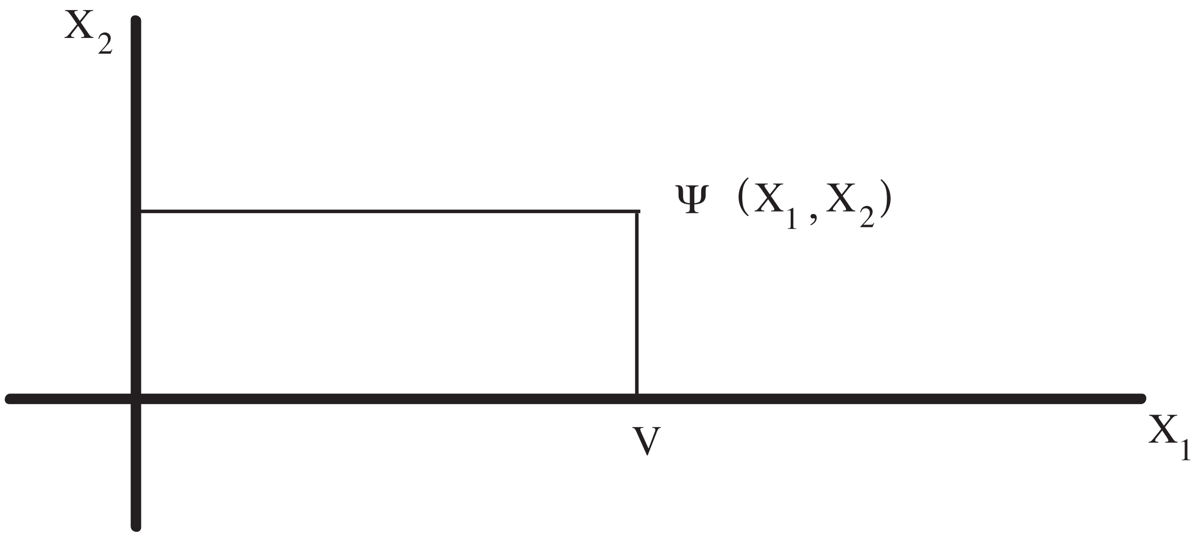
M. BORN

“ Having read this, I relegated the question to the back of my mind and got on with more practical things. But in 1952, I saw the impossible done. It was in papers by David Bohm. Bohm showed explicitly how parameters could indeed be introduced, into nonrelativistic wave mechanics, with the help of which the indeterministic description could be transformed into a deterministic one. More importantly, in my opinion, the subjectivity of the orthodox version, the necessary reference to the ‘observer’, could be eliminated. Moreover, the essential idea was one that had been advanced already by de Broglie in 1927, in his ‘pilot wave’ picture.

But why then had Born not told me of this 'pilot wave' ? If only to point out what was wrong with it ? Why did von Neumann not consider it ? More extraordinarily, why did people go on producing 'impossibility' proofs, after 1952, and as recently as 1978 ? When even Pauli, Rosenfeld, and Heisenberg, could produce no more devastating criticism of Bohm's version than to brand it as 'metaphysical' and 'ideological' ? Why is the pilot wave picture ignored in text books ? Should it not be taught, not as the only way, but as an antidote to the prevailing complacency ? To show that vagueness, subjectivity, and indeterminism, are not forced on us by experimental facts, but by deliberate theoretical choice ? "

J.S. BELL

BUT BOHM IS NONLOCAL



$\mathbb{R}^3 \times \mathbb{R}^3 \to \mathbb{R} \times \mathbb{R} \to (X_1, X_2)$

V = potential around X_1

$\Rightarrow$ Affects $\Psi(X_1, X_2)$ via Schrödinger's Equation

$\Rightarrow$ Affects behaviour of 2^d particle via Guiding Equation

Is the world local ?

- NO
- A PROFOUND RESULT
- SIMPLE TO EXPLAIN
- A MAJOR PROBLEM FOR PHYSICS
- STARTED BY EINSTEIN
- ONE OF THE MOST WIDELY MISUNDERSTOOD RESULT IN PHYSICS
- SOME APPLICATIONS

What is Locality ?

No action at a distance

Properties

1. Instantaneous
2. a. Extends arbitrarily far

   b. does not decrease with distance
3. Individuated
4. Transmits messages

Newton's gravity : 1, 2a and 4

Post-Newtonian physics : 2a and 4

Is there a phenomenon with properties : 1-3

(Not 4 $\longrightarrow$ pseudoscience).

NON LOCALITY

X,Y	Far Apart
A,B,C	3 Questions
Yes/No	2 Answers

Whenever same question on both sides ⇒

always same answer (A, B or C)

Perfect long-distance correlation

+ **NO** Action at a distance whatsoever or " locality "

⇒ ∃ predetermined values (random)

V_x (α), V_y (α), = Yes/No α = A, B, C

BUT

This assumption

(Alone)

is contradicted by observations made when the questions are different.

PROOF

1) $V_x(\alpha) = V_y(\alpha) \qquad \forall\ \alpha = A, B, C$

2) F = Frequency $\qquad V_x, V_y$ = Yes/No $\qquad$ (2 values)

$\alpha = A, B, C \qquad$ (3 values)

V_x, V_y takes 2 values

$\Rightarrow F(V_x(A) = V_x(B)) + F(V_x(A) = V_x(C))$

$+ F(V_x(B) = V_x(C)) \geq 1$

$\Rightarrow$ by 1)

$F(V_x(A) = V_y(B)) + F(V_x(A) = V_y(C))$

$+ F(V_x(B) = V_y(C)) \geq 1$

BUT for suitable experiments

$F(V_x(\alpha) = V_y(\beta)) = 1/4 \qquad \alpha \neq \beta$

$\Rightarrow 3/4 \geq 1$

$\Rightarrow$ Contradiction via no H.V. Theorem

<u>LOGIC</u>

Perfect correlation

+ $\Rightarrow$ values

Locality preexist

No H.V. $\Rightarrow$ $\nexists$ preexisting values

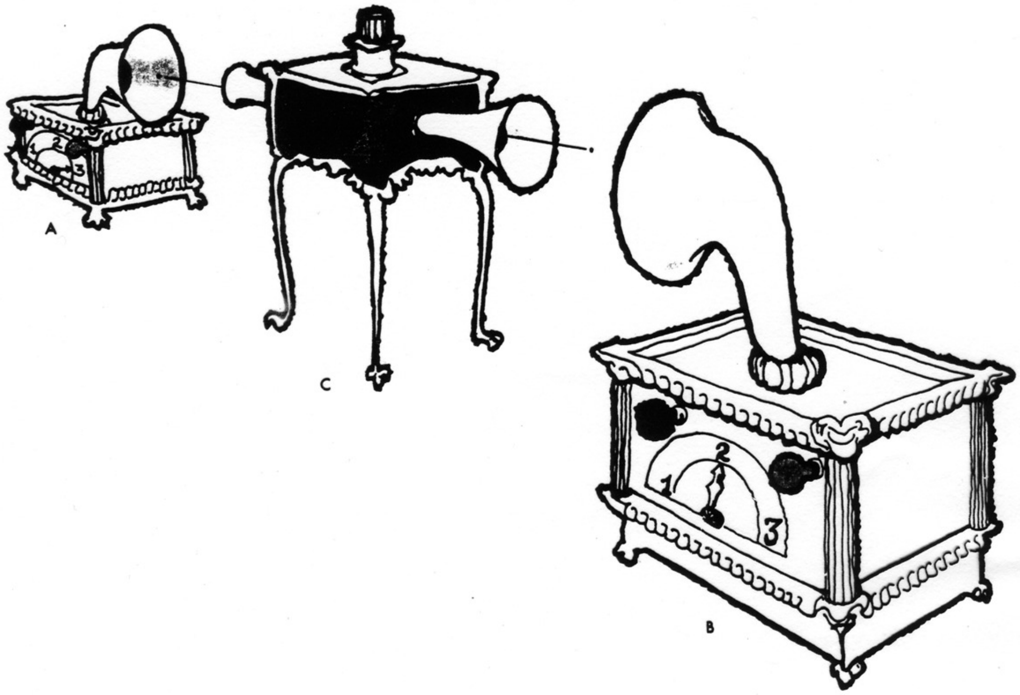
$\Rightarrow$ Loc~~a~~lity

<u>No</u> assumption of

“Determinism”

“Hidden variables”

“Realism”


A
1
2
3
C
1
2
3
B

1, 2, 3 = QUESTIONS (left/right)

Red

Green

≈ 2 ANSWERS (Yes/No)

31RR	22GG	33GG
33GG	11RR	21GR
33RR	33GG	13GR
12GR	31GR	23GR
33GG	12GG	22RR
21GR	21GR	11RR
21RR	33GG	21GR
22RR	21RR	21RR
33GG	12GR	23[illegible]
11GG	22RR	32GR
23RR	13RG	33RR
32GR	12RG	33GG
12GR	23GG	33GG
12RG	11GG	23GR
11GG	13RG	21GR
31RG	21RG	12RR
12RG	33RR	32GR
13GR	32GR	32GR
22GG	32GG	33GG
12RG	33GG	31RG
12GR	21RR	13RR
22GG	12RG	13RG
23GR	22GG	32RG
33RR	11GG	31GR
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32RG	22GG	11RR
21GR	11GG	32RG
22GG	11GG	32GR
22RR	21RG	13GG
13RR	11RR	23GR
21GG	12RG	32GR
23GR	23GR	22RR

35 out of ≈ 130

No superstition result

— Each side observes a perfectly random sequence of Red/Green lights.

— No message is transmitted as such.

— BUT if each side tells the other the list of experiments that were made (1, 2, 3), then they both know the result on the other side when the same experiment has been made on both sides.

⇒ They have then a common sequence of Red/Green i.e. SOME information has been transmitted ‘faster than light’.

Does this conflict with relativity ?

Of course !

At least with the spirit of relativity

R. Penrose: “a tension with relativity”

If some action at a distance exists, then relativity implies some action backward in time.

No (satisfactory) solution.

“ Despite my insistence that the determinism was inferred rather than assumed, you might still suspect somehow that it is a pre-occupation with determinism that creates the problem. Note well then that the following argument makes no mention whatever of determinism. . . Finally you might suspect that the very notion of particle, and particle orbit. . . has somehow led us astray. . . So the following argument will not mention particles. . . nor any other picture of what goes on at the microscopic level. Nor will it involve any use of the words “quantum mechanical system”, which can have an unfortunate effect on the discussion. The difficulty is not created by any such picture or any such terminology. It is created by the predictions about the correlations in the visible outputs of certain conceivable experimental set-ups ”

J. BELL

“ Let me summarize once again the logic that leads to the impasse. The EPRB correlations are such that the result of the experiment on one side immediately foretells that on the other, whenever the analyzers happen to be parallel. If we do not accept the intervention on one side as a causal influence on the other, we seem obliged to admit that the results on both sides are determined in advance anyway, independently of the intervention on the other side, by signals from the source and by the local magnet setting. But this has implications for non-parallel settings which conflict with those of quantum mechanics. So we *cannot* dismiss intervention on one side as a causal influence on the other ”

J. BELL

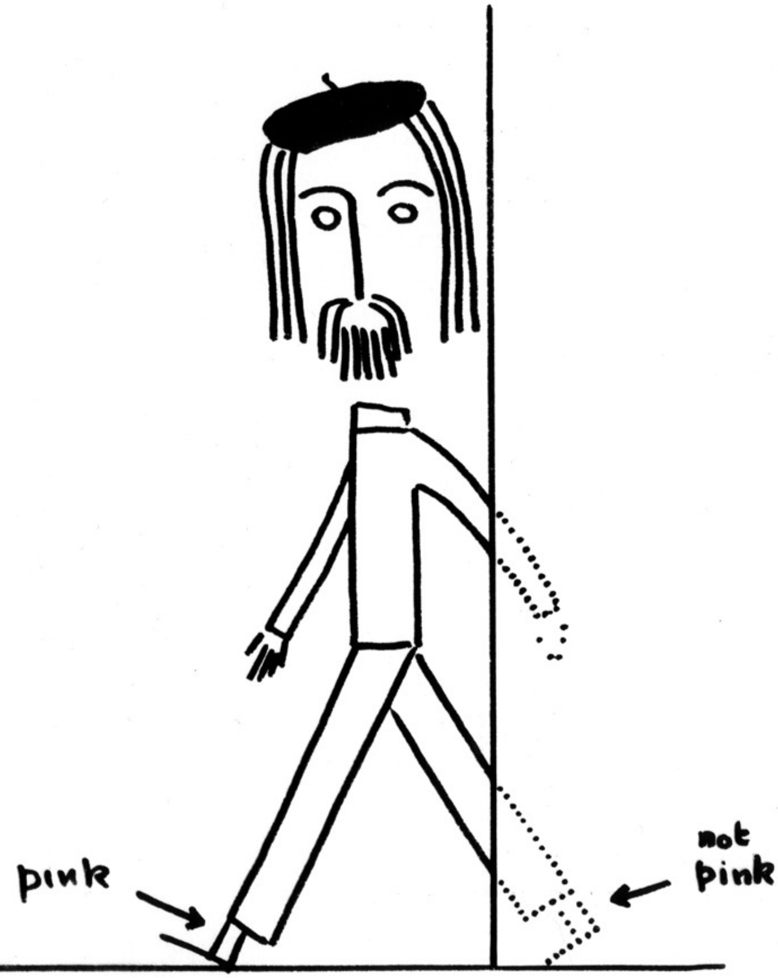
“ for more than forty years, David [Bohm] tried to reformulate and reinterpret quantum mechanics so as to overcome his doubts”,... “some theoretical work of John Bell revealed that the EPRB experimental setup could be used to distinguish quantum mechanics from hypothetical hidden variable theories... After the publication of Bell’s work, various teams of experimental physicists carried out the EPRB experiment. The result was eagerly awaited, although virtually all physicists were betting on the corrections of quantum mechanics, which was, in fact, vindicated by the outcome ”

M. GELL-MANN

Fig 1

Les chaussettes de M. Bertlmann et la nature de la réalité

Fondation Hugot
juin 17 1980



“ The situation is like that of Bertlmann’s socks, described by John Bell in one of his papers. Bertlmann is a mathematician who always wears one pink and one green sock. If you see just one of his feet and spot a green sock, you know immediately that his other foot sports a pink sock. Yet no signal is propagated from one foot to the other. Likewise no signal passes from one photon to the other in the experiment that confirms quantum mechanics. No action at a distance takes place ”

MURRAY GELL-MANN

“ The proof he [von Neumann] published... though it was made much more convincing later on by Kochen and Specker, still uses assumptions which, in my opinion, can quite reasonably be questioned... In my opinion, the most convincing argument against the theory of hidden variables was presented by J.S. Bell ”

E. WIGNER

I know that most men, including those at ease with problems of the highest complexity, can seldom accept even the simplest and most obvious truth if it be such as would oblige them to admit the falsity of conclusions which they have delighted in explaining to colleagues, which they have proudly taught to others, and which they have woven, thread by thread, into the fabric of their lives

TOLSTOY

My interest has always been to understand what the world is like. This is the main reason that I majored in physics: if physics is the study of nature, then to understand nature one should learn physics first. But my hopes were disappointed by what is (or at least seems to be) commonly accepted in many physics departments all over the world: after quantum mechanics, we should give up the idea that physics provides us with a picture of reality. At first, I believed this was really the case and I was so disappointed that I decided to forget about my 'romantic' dream ...

At some point, …I realized that some of the things I took for granted were not so obviously true, and I started to regain hope that quantum mechanics was not really the "end of physics" as I meant it. Therefore, I decided to go to graduate school in physics to figure out what the situation really was. While taking my Ph. D. in the foundations of quantum mechanics, I understood that what physicists thought was an unavoidable truth was instead a blunt mistake: quantum mechanics does not force us to give up anything, and certainly not the possibility to investigate reality through physics.

V. ALLORI