# WHAT EXACTLY DO THE "EPR-BELL" EXPERIMENTS TELL US ABOUT THE WORLD? (OR: LOCALITY, "REALISM" AND ALL THAT)

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1. What is realism in physics? ≅ macroscopic counterfactual definiteness (MCFD)

2. Recap of EPR-Bell experiments, and one standard analysis thereof (based on locality plus realism/MCFD)

3. The "collapse locality" loophole: alternative refutation of MCFD

4. Is locality enough? (Gisin): macroscopic counterfactual quasi definiteness.

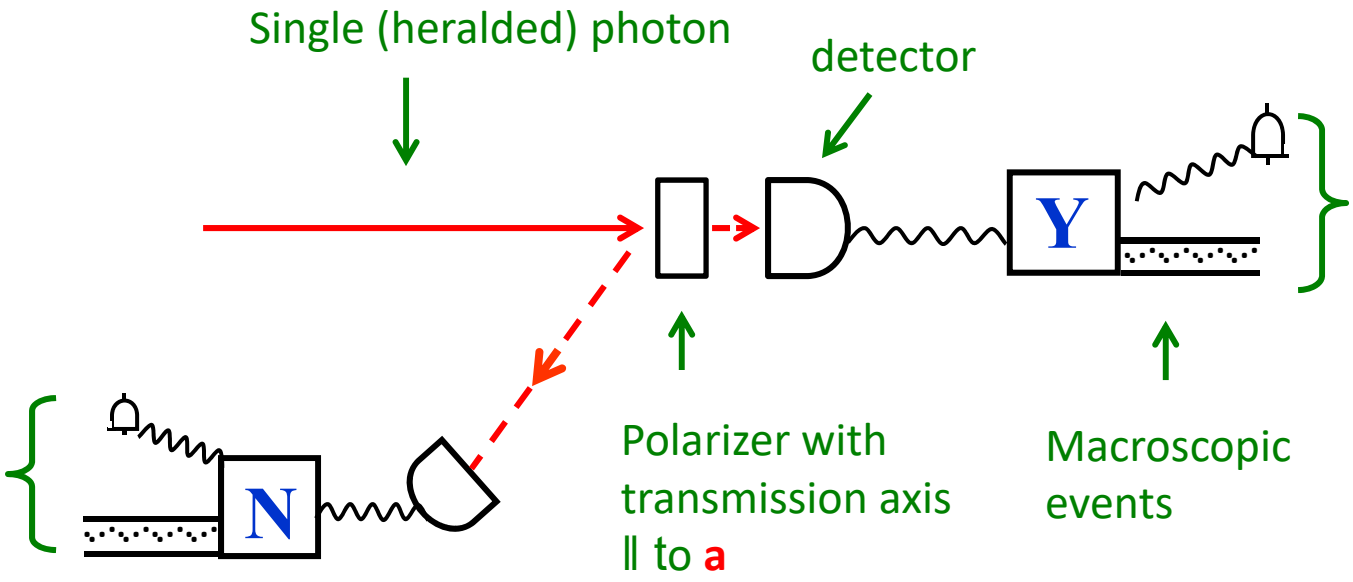
5. Conclusion

# 1. WHAT DO WE/CAN WE MEAN BY "REALISM" IN PHYSICS?

Tentative definition of "realism":

At any given time, the world has a definite value of any property which may be measured on it (irrespective of whether that property actually is measured)

(Microscopic) example: photon polarization




"Question" posed to photon:

Are you polarized along **a**?

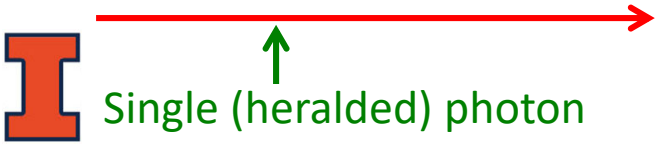
Experimental fact:

for each photon, either counter Y clicks (and counter N does not) or N clicks (and Y does not).

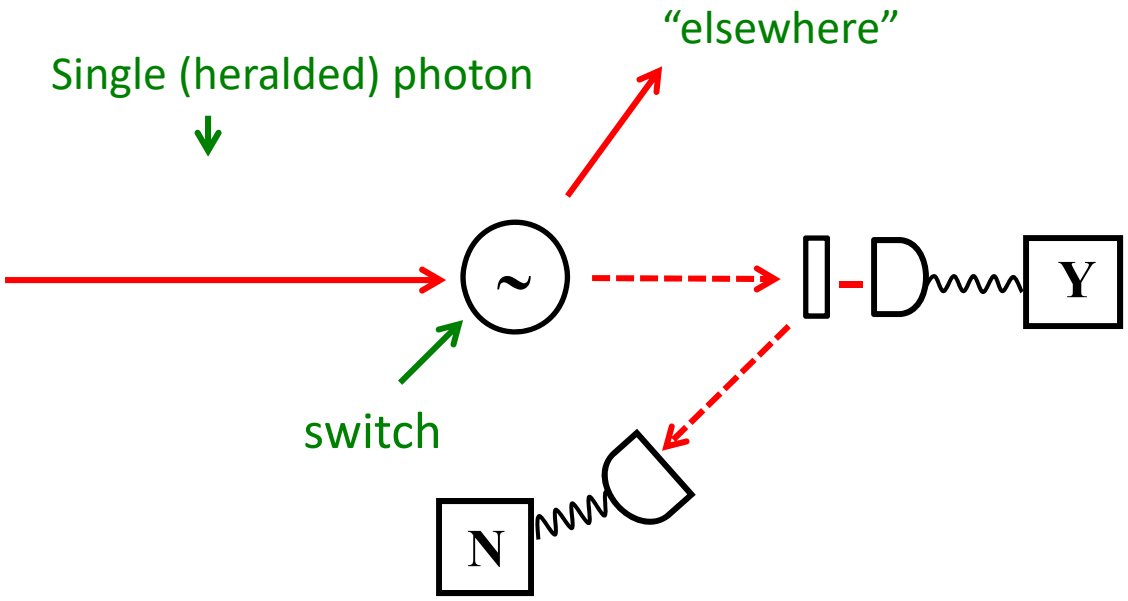
natural "paraphrase":

when asked, each photon answers either "yes" (A = +1) or "no" (A = -1)

But: what if it is not asked?



# MACROSCOPIC COUNTERFACTUAL DEFINITENESS (MCFD)
(Stapp, Peres…)




Suppose a given photon is directed "elsewhere".
What does it mean to ask "does it have a definite value of A?"?
A possible quasi-operational definition:
Suppose photon had been switched into measuring device:
Then:
Proposition I (truism?): It is a fact that either counter Y would have clicked (A = +1) or counter N would have clicked (A = -1)

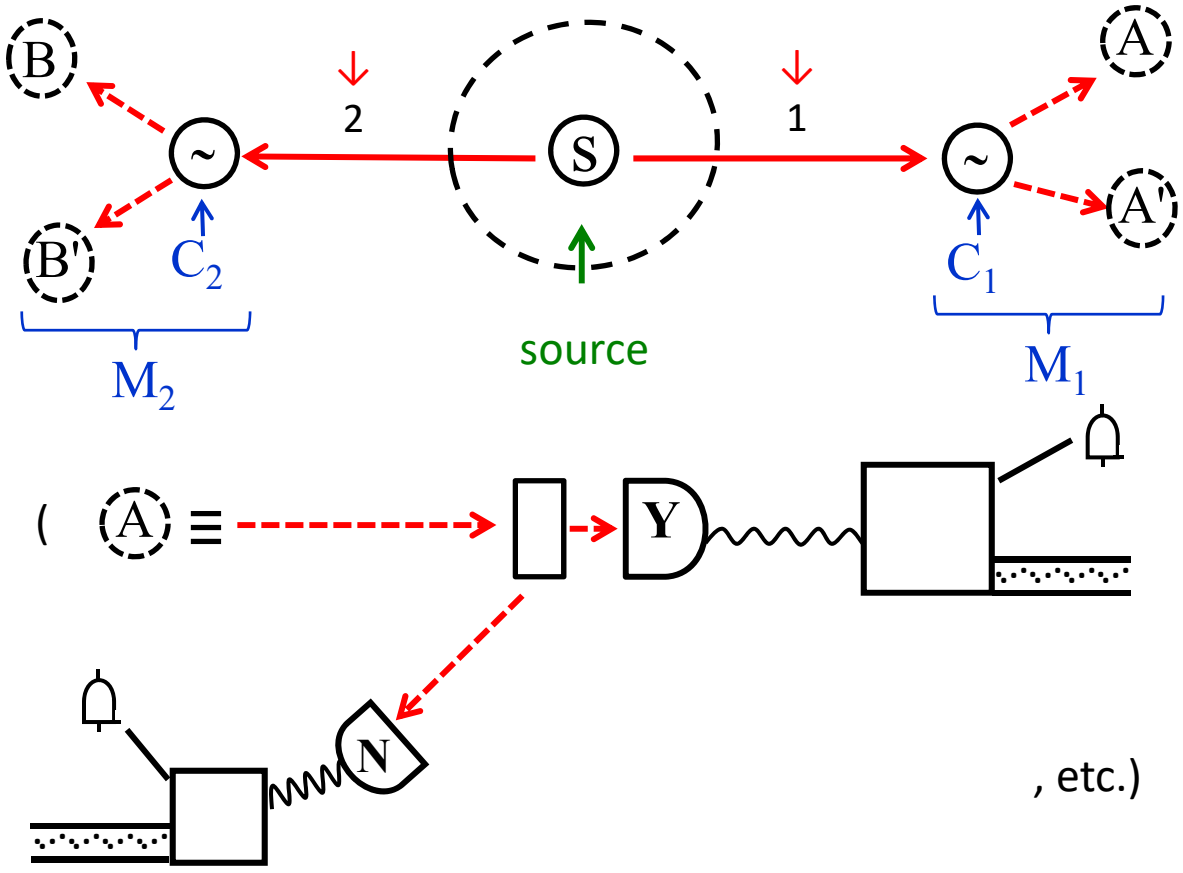
⇓ ?

Proposition II (MCFD): Either it is a fact that counter Y would have clicked (i.e. it is a fact that A = +1) or it is a fact that counter N would have clicked (A = -1)

Realism ≅ proposition II?

(will take as definition of "realism" for purposes of present talk)

## 2. THE EPR-BELL EXPERIMENTS (idealized)




Df: if object 1 is directed into counter A and counter A clicks, $A \equiv +1$ (etc.)
" " " " does not click, $A \equiv -1$

CHSH inequality: all objective local theories (OLT's) satisfy the constraints

$$\langle AB\rangle_{exp} + \langle A'B\rangle_{exp} + \langle AB'\rangle_{exp} - \langle A'B'\rangle_{exp} \leq 2 \qquad (*)$$

(*) is violated (by predictions of QM, and) (prima facie)
by experimental data.

Note: for purposes of refuting local realism, use of "source" is inessential! (correlations can be generated any way we please).

Objective local theories (OLT's) defined by conjunction of

(1) Realism ("objectivity") – physical systems have definite properties whether or not these are observed. (will replace by MCFD)

(2) Locality – no causal influence can propagate with velocity > c ← speed of light

(3) *Absence of retrocausality ("induction"): future cannot affect present/past
(will not question in this talk)

So: experimental refuation of CHSH inequality ⇒
either locality or realism (MCFD) false (or both)

*[Note: in SR (2) →(3), but we want to consider more general scenarios]

## Proof of CHSH inequality:

1. By (1) for any given pair, quantities A, B, A′, B′ exist and take values $\pm 1$. (realism)

2. By (2) and (3), value of A independent of whether B or B′ measured at distant station (and vice versa) (locality)

3. Hence for any given pair, the quantities
   AB, AB′ etc. exist, with A taking the same value ($\pm 1$) in AB and in AB′ (etc.)

4. Then grade-school algebra $\Rightarrow$
   $AB + A'B + AB' - A'B' \leqslant 2$

5. Thus when measured on same ensemble,
   $\langle AB \rangle + \langle A'B \rangle + \langle AB' \rangle - \langle A'B' \rangle \leqslant 2$

6. While strictly speaking we should write the experimentally measured correlation as
   $\langle AB \rangle_{exp} \equiv \langle AB \rangle_{AB}$ ,
   ↑ ensemble on which A and B measured
   by (3) $\langle AB \rangle_{AB} = \langle AB \rangle_{AB'}$ , etc. $\equiv \langle AB \rangle$ (induction)

7. Hence
   $\langle AB \rangle_{exp} + \langle A'B \rangle_{exp} + \langle AB' \rangle_{exp} - \langle A'B' \rangle_{exp} \leqslant 2$ , QED.

noncontroversial

3. Experimental fact: experiments of Nov – Dec 2015 prima facie refute CHSH inequality* with claimed statistical significance of $<10^{-30}$ and all the "standard" loopholes blocked.

⇒ local realism is dead?

What are the outstanding loopholes?

(1) Superdeterminism probably untestable

(2) retrocausality probably untestable

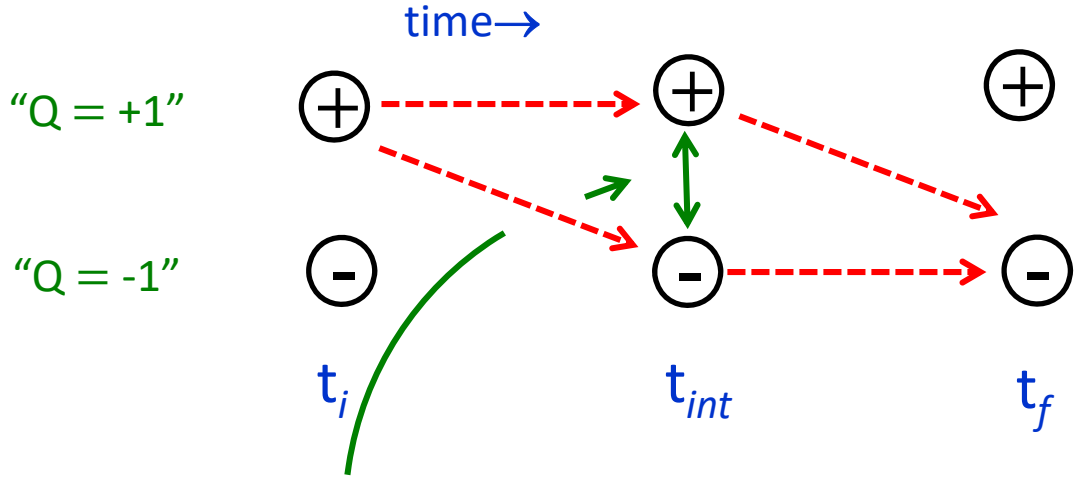
(3) collapse locality ?

at what point in the "measurement" process was a definite outcome realized?
Can experiment (of a different kind) say anything about this?

*(or the Eberhard generalization thereof)

## MACROSCOPIC QUANTUM COHERENCE (MQC)

**QM:**




macroscopically distinct* states

Example: "flux qubit":


QM: at $t_{int}$, state is quantum superposition of ⊕ and ⊖

Macrorealism (≡ MCFD): at $t_{int}$, either ⊕ or ⊖
Can we test this hypothesis? Yes!

* how "macroscopically" distinct?
(cf: arXiv: 1603.03992)

NTT experiment

Rather than measuring 2-time correlations, check directly how far measurement (not necessarily noninvasive) at $t_2$ affects $\langle Q(t_3)\rangle \equiv \langle Q_3\rangle$ for the different macroscopically distinct states and for their (putative) quantum superposition.

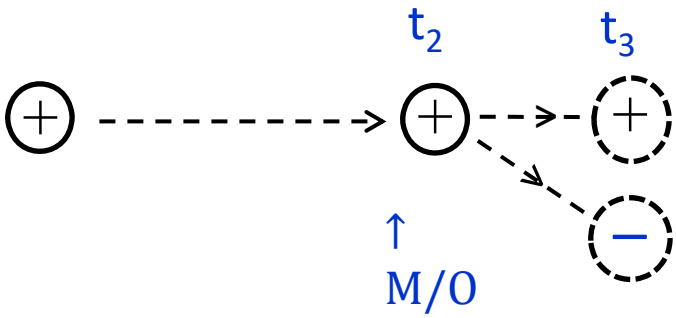
Define for any state $\sigma$ at $t=t_2-$,

$$d_\sigma \equiv \langle Q_3\rangle_M - \langle Q_3\rangle_O$$

$M \equiv$ measurement with uninspected outcome made at $t_2$

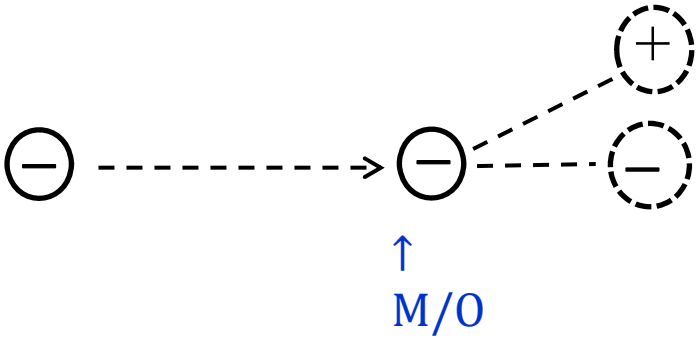
$O \equiv$ measurement not made at $t_2$

Ancillary test: $\sigma = \oplus$



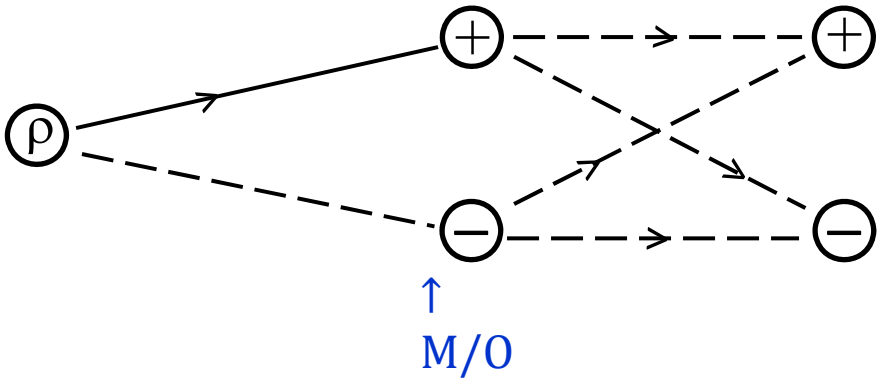

$$d_+ \equiv \langle Q_3\rangle_M - \langle Q_3\rangle_O$$

$\sigma = \ominus$




$$d_- \equiv \langle Q_3\rangle_M - \langle Q_3\rangle_O$$

Knee et al. experiment*:




$d_\rho \equiv \langle Q_3 \rangle_M - \langle Q_3 \rangle_0$

Df: $\delta \equiv d_\rho - \min(d_+, d_-)$

MR: $\delta > 0$

macrorealism

Expt: $\delta = -0.063$

violates MR prediction by > 84 standard deviations!

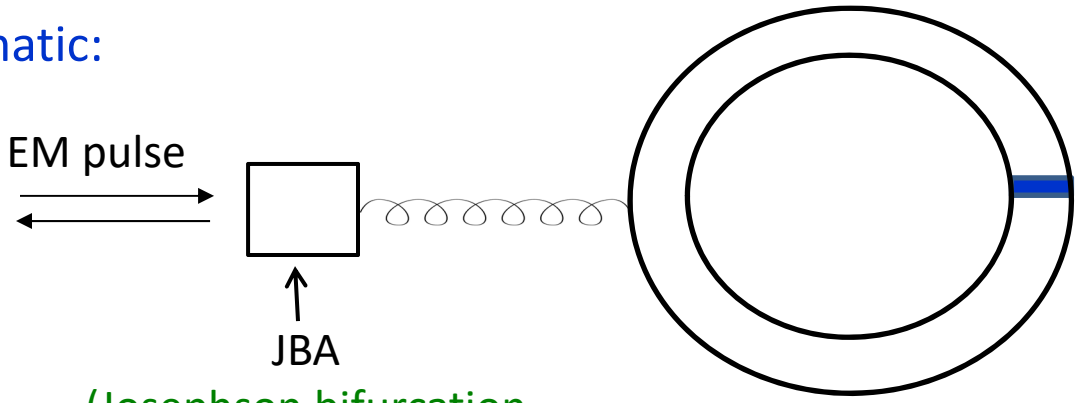
So: had better take "collapse locality" loophole seriously!

*G.C. Knee et al. (including AJL) Nature Communications **7**, 13253 (2016)

The irony is: when the rf SQUID (flux qubit) was originally invented in the 60's, its principal role was as a measuring device for magnetic flux! Originally, such flux was highly classical, but to-day, sensitivity is ~ 300 spins, and in future envisaged to be single spin. Thus can act as the "measuring device" in the von Neumann scheme.

To employ flux qubit as such (and for some steps in the Knee et al. protocol) must be able to read off value of Q. How to do this?

Schematic:




If we wish to measure Q at time t, inject EM pulse into JBA.
If we do not wish to measure Q at time t, don't inject anything!

If pulse injected, Q is definite.
If pulse not injected, Q is indefinite!

Thus, Knee et al. experiment can be regarded as
direct refutation of MCFD

But, why should we believe MCFD in the first place?

Recap: our tentative definition of "realism" was by proposition II.

Either it is a fact that counter Y would have clicked, or it is a fact that counter N would have clicked.

This is the statement of macroscopic counterfactual definiteness. So:

Do counterfactual statements have truth-values? (common sense, legal system... assume so!)

A possible view on the meaning of counterfactuals*

"If kangaroos had no tails, they would topple over" seems to me to mean something like this: in any possible state of affairs in which kangaroos have no tails, and which resembles our actual state of affairs as much as kangaroos having no tails permits it to, the kangaroos topple over.

*David K. Lewis, Counterfactuals, Harvard U.P. 1975

So... is it the case that in any experiment in which “everything else is the same” but we measure A instead of A´, we always get (say) +1?

Alas, no!  (and NTT experiment shows this is not simply “amplification” of a microscopic indeterminacy, it is true even at a (semi-) macroscopic level).

But, back to EPR-Bell…

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# Non-realism: Deep Thought or a Soft Option?

**Nicolas Gisin**

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**Abstract** The claim that the observation of a violation of a Bell inequality leads to an alleged alternative between nonlocality and non-realism is annoying because of the vagueness of the second term.

**Keywords** Nonlocality · Bell inequality · Realism · Measurement problem

## 1 Introduction

In recent years the violation of Bell's inequality has often been interpreted as either a failure of locality or of realism (or of both). The problem with such a claim is that it is not clear what realism in this context should mean. In this note my goal is to look for a definition of realism compatible with the claim that it has been falsified.[1] Sometimes realism is defined as the hypothesis that every physical quantity always has a value.[2] But then, either this value is unaccessible, hence unphysical, or this value can be revealed by appropriate measurements (to arbitrary good approximation, at least in principle). Hence, these measurements have predetermined outcomes and realism is nothing but a fancy word for determinism. If so, first, why should one use the word local realism instead of local determinism? And second, Bell's inequality can be stated and proved without any assumption about determinism.

[1] My personal definition of realism—that clearly has not been falsified—is another issue. For me realism means [2], very briefly, that physical systems possess properties preexisting and independent of whether we measure the system or not; however these preexisting properties do not determine measurement outcomes, but only their propensities. Accordingly, there are realistic random events that reflect preexisting properties, as required by realism, simply the reflection is not deterministic.

[2] For example, in [1] A. Zeilinger at al. define realism as "the assumption that measurement outcomes are well defined prior to and independent of the measurements".

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Gisin's second claim:

To prove CHSH inequality, it is adequate to postulate the locality condition

$\forall$ a,b,$\lambda$

Prob. that both A and B stations register "Y"

$$p_{++}(\mathbf{a},\mathbf{b},\lambda) = p_{+}(\mathbf{a},\lambda)\, p_{+}(\mathbf{b},\lambda) \qquad \text{(etc. for } p_{+-}, \ldots) \qquad (*)$$

polarizer settings

Specification of 2-photon state (not necessarily by "hidden variable")

Once (*) is granted, algebra to obtain CHSH inequality is trivial.

However:

what does $p_{++}(\mathbf{a},\mathbf{b},\lambda)$ actually mean?

For any given pair of photons, **a,b** (by experimental construction) and $\lambda$ (by assumption) take definite values. However, we need to postulate (*) also for values which are not taken, e.g. for $p_{++}(\mathbf{a}',\mathbf{b},\lambda)$! At least for continuous $\lambda$, cannot define this quantity in frequentist terms: it must refer to, not one, but a whole collection of experiments which we have not conduced:

"had we measured the results of a large ensemble of experiments with setting **a′,b** and state description $\lambda$, the distribution of (++) results would have been statistically consistent with the "value" $p_{++}(\mathbf{a}',\mathbf{b},\lambda)$" – i.e. not one, but a whole set of counterfactual statements.

⇒ "macroscopic counterfactual quasidefiniteness" (MCFQD)

The $64K question:

Is MCFQD anymore acceptable than MCFD?

SO, IN THE LAST RESORT, WHAT (EXACTLY) DO THE "EPR-BELL" EXPERIMENTS TELL US ABOUT THE WORLD?

MAYBE (PERES) THAT

UNPERFORMED EXPERIMENTS HAVE NO RESULTS (EVEN STATISTICAL ONES).