“Realism” and the Physical World:

Implications of Some Recent Experiments

Distinguished Bhaumik Lecture

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“Had I woken up 5 minutes earlier this morning, I would have caught the 8:00 bus.”

What do we/can we mean by "realism"?

Philosophers discuss "reality" of (e.g.)

the human mind
the number 5
moral facts
atoms (electrons, photons…)
……..

} but, difficult to think of input from physics

So: in what sense can physics as such say something about "realism"?

(My) proposed definition:

> 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)

To make this proposition (possibly) experimentally testable, need to extend it to finite "parts" of the world.

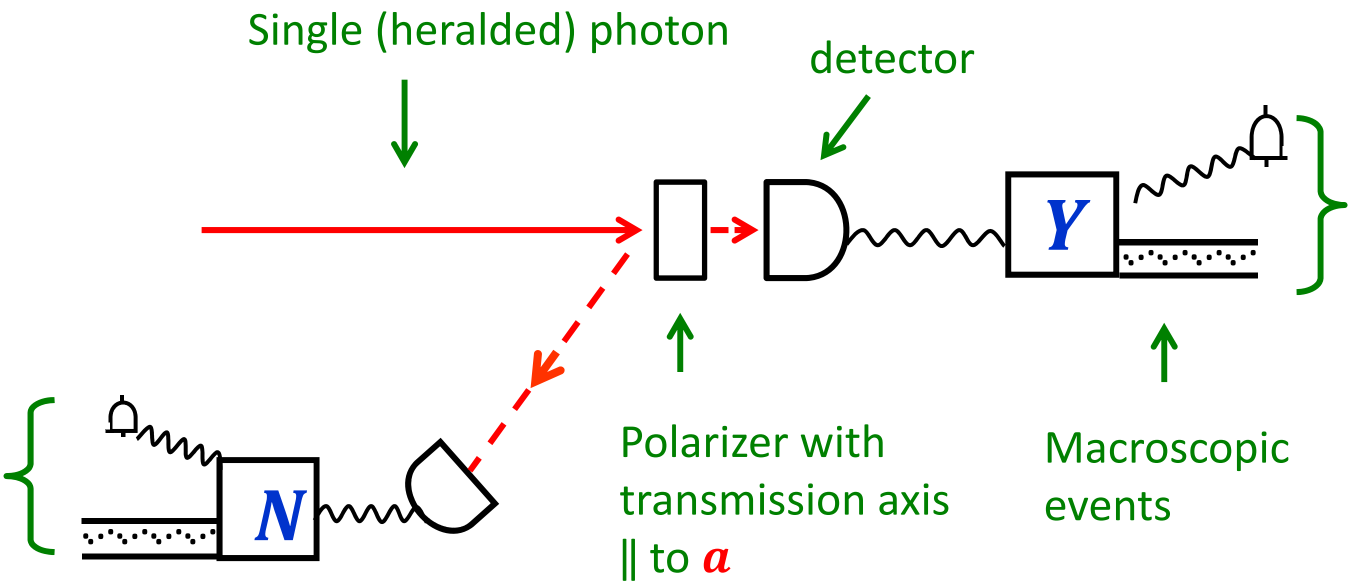
Irrespective of the universal validity (or not) of QM, what can we infer about this proposition

directly from experiment?

QM ← quantum mechanics

THE SIMPLEST CASE: A TWO STATE SYSTEM

(Microscopic) example: photon polarization



"Question" posed to photon:

Are you polarized along $\boldsymbol{a}$?

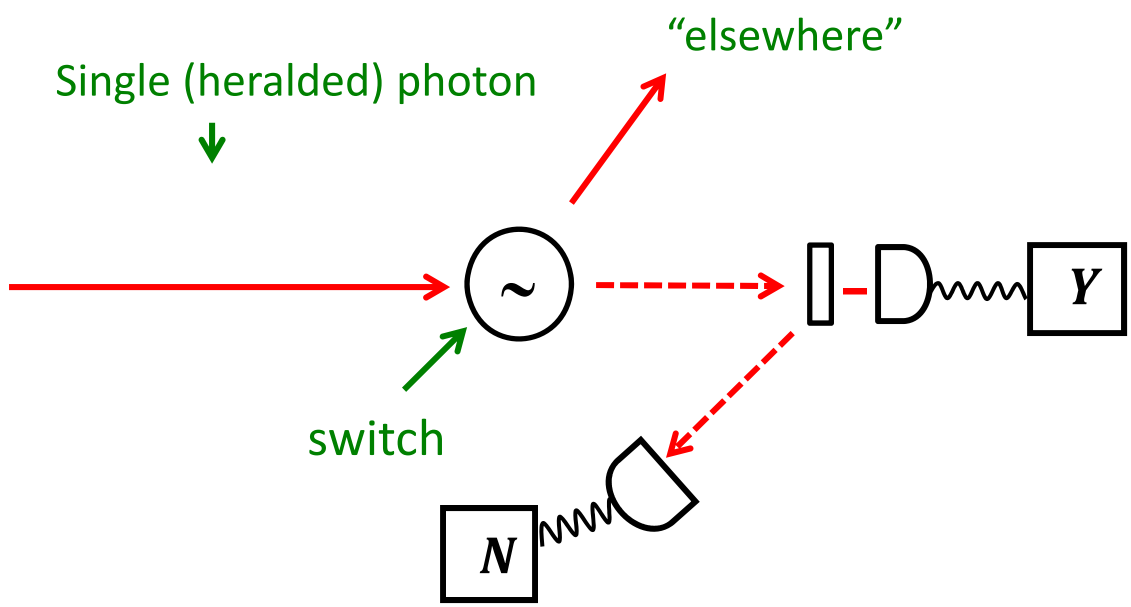
Experimental fact:

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

natural "paraphrase":

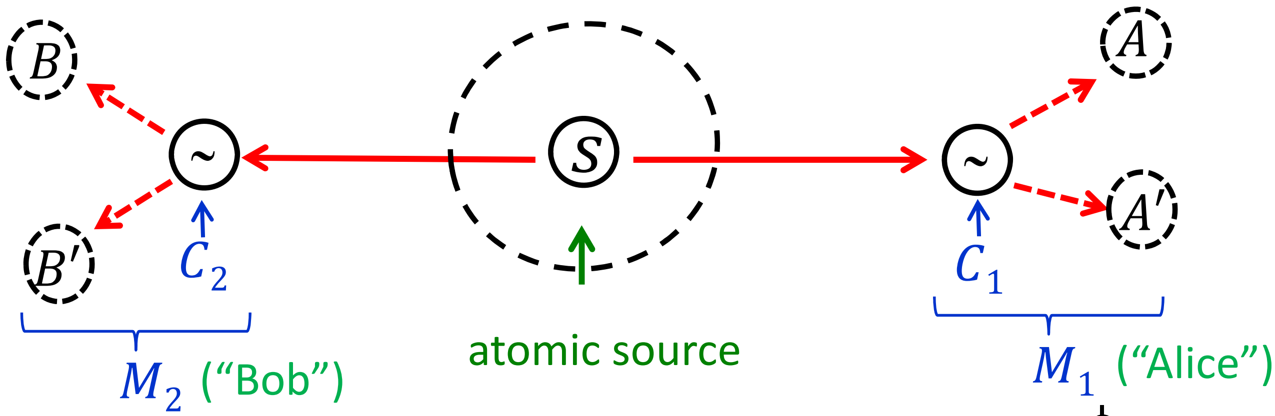
when asked, each photon answers either "yes" ($A = +1$) or "no" ($A = -1$)

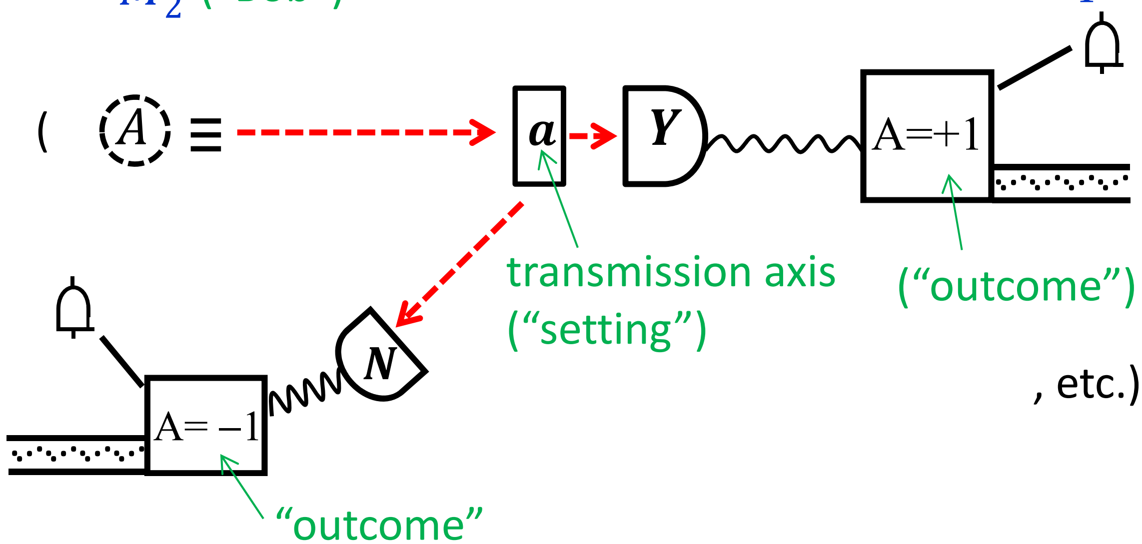
But: what if it is not asked?



Suppose a given photon is directed "elsewhere". Does it have a definite value of A? What does this question **mean**?

THE EPR-BELL EXPERIMENTS (idealized)





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

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

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

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

What do the (idealized) EPR-Bell experiments show?

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

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

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

(3) *Absence of retrocausality ("induction"): future cannot affect present/past ⇒ ensembles characterized by initial conditions (preparation) only

Special relativity ↙

*[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 ± 1.

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

3. Hence for any given pair, the quantities
   AB, AB' etc. exist, with A taking the same value (± 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
   $\langle AB \rangle_{\text{exp}} \equiv \langle AB \rangle_{AB}$, by (3) $\langle AB \rangle_{AB} = \langle AB \rangle_{AB'}$, $etc. \equiv \langle AB \rangle$

   ↑ ensemble on which A and B measured

   so can write $\langle AB \rangle = \langle AB \rangle_{\text{exp}}$

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

Thus, prima facie: at least one of (1) – (3) must fail.
Locality? Induction? Or…

Digression:

: Is assumption (1) (“realism”) actually needed for derivation of CHSH inequality? If not, then rejection of it will not help (we would still need to reject either locality or induction, or both)

Gisin* claims no: that it is enough to assume that for any given “state” λ (λ is not necessarily a hidden variable!) we have the “locality” relations

$$p(A|\boldsymbol{a},\boldsymbol{b}|\lambda) = p(A{:}\,\boldsymbol{a},\lambda) \quad , p(B|\boldsymbol{a},\boldsymbol{b}{:}\,\lambda) = p(\boldsymbol{B}|\boldsymbol{b},\lambda)$$

Alice’s outcome (A), Alice’s setting ($\boldsymbol{a}$), Bob’s setting ($\boldsymbol{b}$), Bob’s outcome (B)

so that

$$p(A,B{:}\,\boldsymbol{a},\boldsymbol{b}) = \int d\lambda\, \rho(\lambda)\, p(A|\boldsymbol{a}\lambda)p(B|\boldsymbol{b},\lambda)$$

$\rho(\lambda)$: distribution of parameter λ

At first sight, these assumptions are sufficient to permit derivation of CHSH inequality.

*N. Gisin, “Non-realism: deep thought or a soft option?”, Found. Phys. **42**, 80 (2012)

However:

Suppose $\rho(\lambda) = \sum_{i=1}^{N_\lambda} \rho_i \, \delta(\lambda - \lambda_i)$, so that

← total number of values of λ

$$p(A, B: \boldsymbol{a}, \boldsymbol{b})_{exp} = \sum_{j=1}^{N_r} p\left(A|\boldsymbol{a}, \lambda_j\right) p\left(\boldsymbol{B}|\boldsymbol{b}, \lambda_j\right)$$

← total number of runs

Problem: if $N_\lambda \gg N_r$, the pairs (e.g.) AB and AB' are never measured for the same value λ_j of λ! so derivation of CHSH fails (and this is always so for continuous λ)

If this is right, assumption (1) is necessary, which in turn means if following experimental refutation of CHSH we want to keep assumptions (2) (locality) and (3) induction, we can do so, but must then reject (1) (realism)

The most obvious "loopholes" in EPR-Bell experiments (pre- 11/15)

(1) "locality": event of (e.g.) switching at C_1 not spacelike separated from detection in M_2

(2) "freedom of choice": switching at $C_{1,2}$ may not be truly "random"

(3) "detection": if counters not 100% efficient, detected particles may not be representative sample of whole.

Until Nov. 2015, many experiments had blocked 1 or 2 loopholes, but none had blocked all 3 simultaneously.

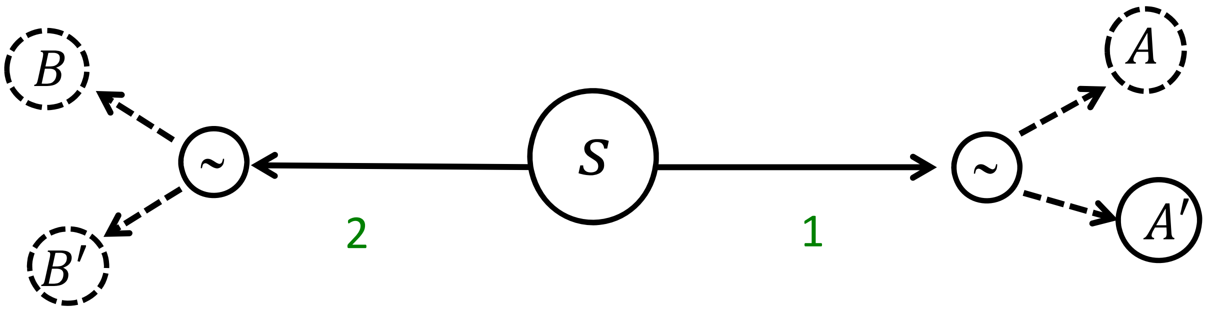
Why?

Blocking of (1) requires spacelike separation of switching at C_1 and detection at M_2
and blocking of (2) requires (inter alia) spacelike separation of switching at C_1 and emission at S (or equivalent)
} easy for photons, difficult for e.g. atoms

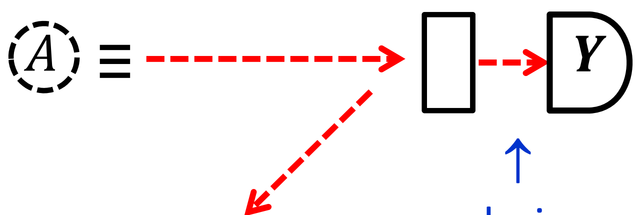
Blocking of (3) requires detector efficiency >82.8% for CHSH (or 67% for Eberhard, see below) — easy for atoms, etc., difficult for photons

To exclude giant "conspiracy of Nature" need to block all 3 loopholes simultaneously! ("holy grail" of experimental quantum optics)

A useful extension of CHSH inequality (Eberhard):



but now:



(etc.)

↑
polarizer
set in direction
$\boldsymbol{a}$

(so don't mind whether nondetected particles had polarization $\perp$ $\boldsymbol{a}$, or were simply not detected because of inefficiency of counter).

Eberhard inequality:

$$J \equiv p(++|ab) - p(+O|ab') - p(O+|a'b) - p(++|a'b') \leq O$$

where, e.g.,

$p(+O|ab) \equiv$ probability that with particles switched into detectors A, B, detector A fires and B does not.

Inequality is valid independently of detection efficiency η, but predictions of QM violate it only for $\eta > 67\%$.

EPR-Bell Experiments of Nov – Dec. 2015

First author affiliation	System	$C_1 - M_2$ distance	Inequality tested	Value of (K – 2) or J	Quoted significance
Delft	electron spins	1.3 km	CHSH	0.42	0.019/0.039
NIST	photon polarization	185m	Eberhard	2×10^{-7}	$<2.3 \times 10^{-3}$
IQOQI	photon polarization	58m	Eberhard	7×10^{-7}	$<10^{-30}$[sic!]

⇒ local realism is dead?

What are the outstanding loopholes?

(1) Superdeterminism — probably untestable

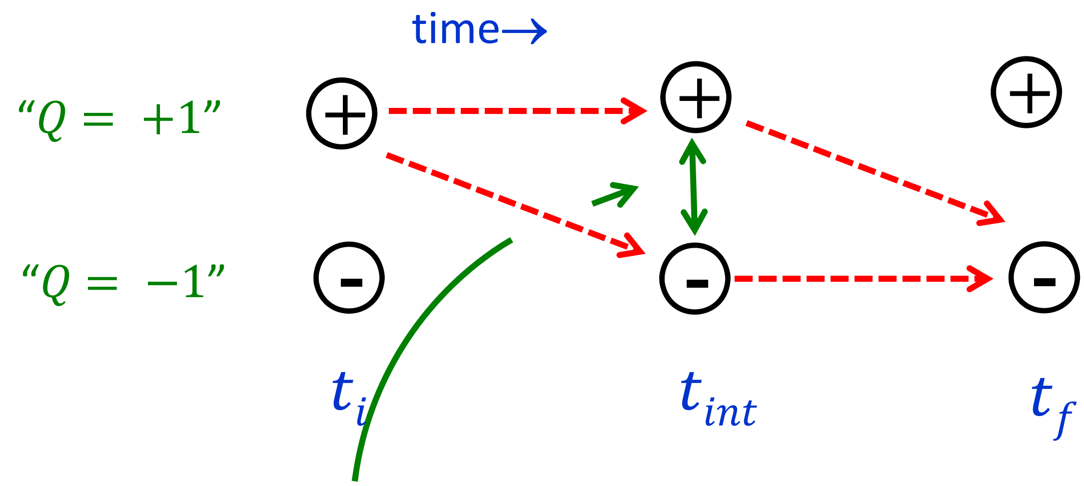
(2) retrocausality — probably untestable

(3) collapse locality — ?

at what point in the "measurement" process was a definite outcome realized?

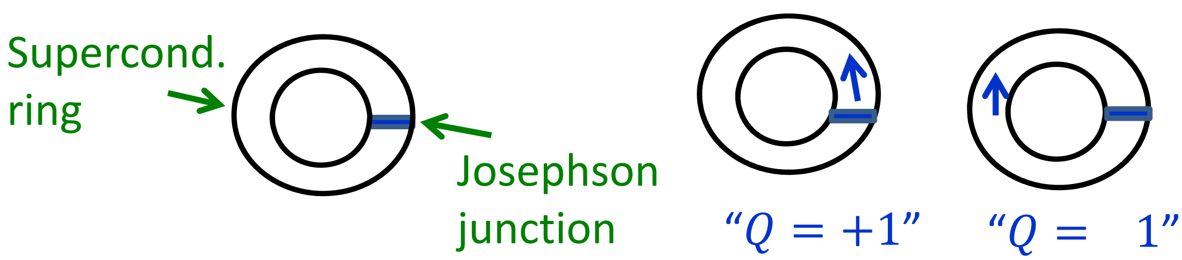
Can experiment (of a different kind) say anything about this?

MACROSCOPIC QUANTUM COHERENCE (MQC)



macroscopically
distinct states

Example: "flux qubit":



Pre-Dec. 2016 experiments: if raw data interpreted in QM terms, state at t_{int} is quantum superposition (not mixture!) of states ⊕ and ⊖ .

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

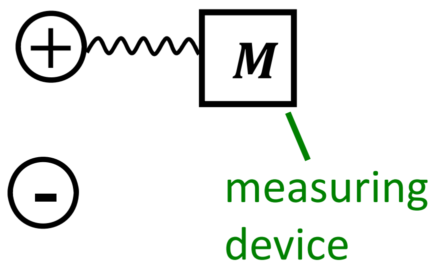
Definition of "macrorealistic" theory: conjunction of

1) macrorealism "per se" ($Q(t) = +1$ or -1 for all t)

2) absence of retrocausality

3) noninvasive measurability (NIM) [substitutes for locality in CHSH]

NIM:



If $Q = +1$, throw away
If $Q = -1$, keep

In this case, unnatural to assert 1) while denying 3). NIM cannot be explicitly tested, but can make "plausible" by ancillary experiment to test whether, when $Q(t)$ is known to be (e.g.) $+1$, a putatively noninvasive measurement does or does not affect subsequent statistics. But measurements must be projective ("von Neumann").

Pre-Dec. 2016 experiments use "weak-measurement" techniques (and states are not macroscopically distinct)

NTT experiment*

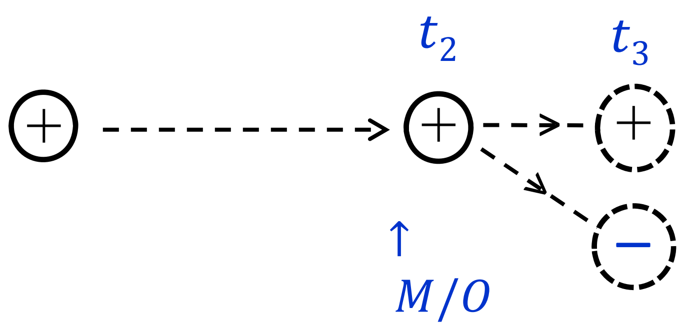
Rather than measuring 2-time correlations, check directly how far measurement (not necessarily noninvasive) at t_2 affects $\langle Q(t_3)\rangle \equiv \langle Q_3\rangle$ for the different macroscopically distinct states and for their (putative) quantum superposition.

Define for <u>any</u> state σ at $t = t_2 -$,

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

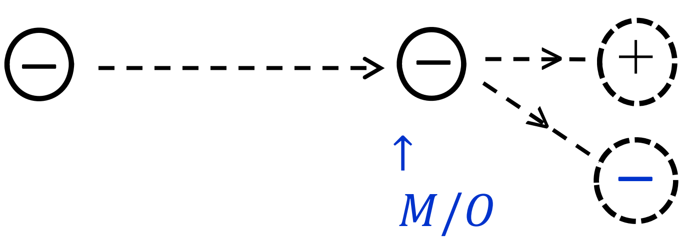
- $M \equiv$ measurement with uninspected outcome made at t_2
- $O \equiv$ measurement not made at t_2

Ancillary test: $\sigma = \oplus$



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

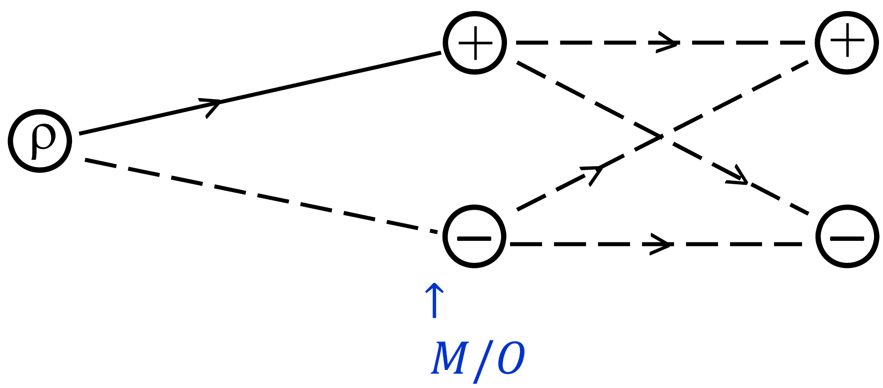
$\sigma = \ominus$



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

*G.C. Knee, et al., Nature Communications, DOI:10.1038/ncomms13253 (2016)

Main experiment:



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

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

MR: $\delta > 0$

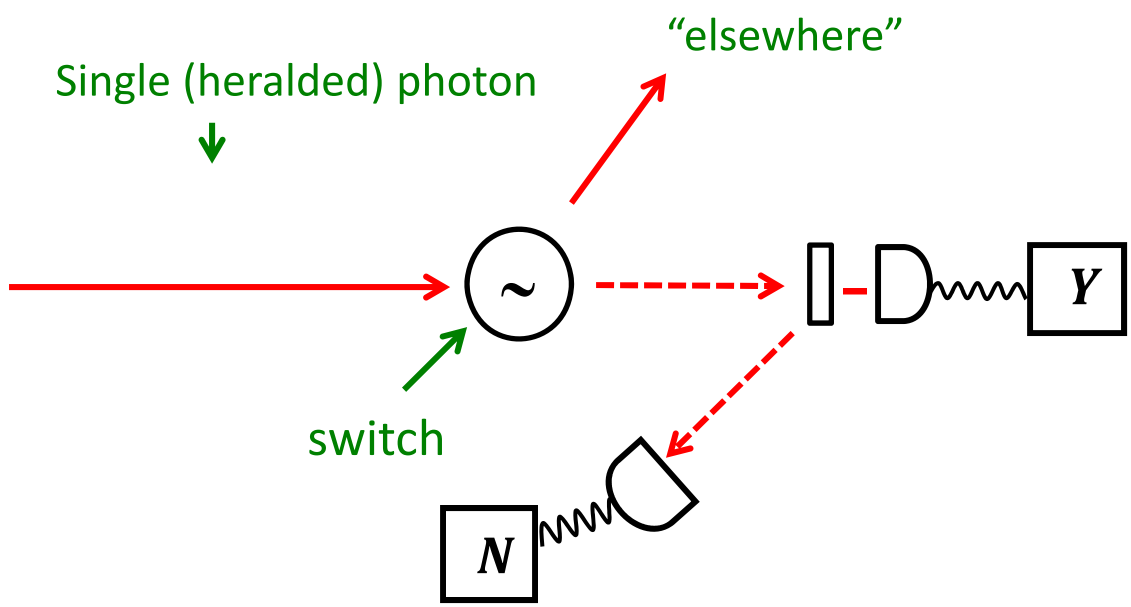
Expt: $\delta = -0.063$

violates MR prediction by $>$ 84 standard deviations!

So, it seems that realism is refuted at both the microscopic and the (putatively) macroscopic level. But what does this mean?

(“it depends what the meaning of ‘is’ is”)

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 ($A = -1$)

$$\Downarrow \; ?$$

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 $\cong$ proposition II?

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.

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). Is determin**acy** even possible in the absence of determin**ism**?

Either way, we may eventually have to conclude...

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

EVEN AT THE EVERYDAY LEVEL,

THERE IS NO SUCH THING AS

“WOULD HAVE”!