Realism Versus Quantum Mechanics:

Implications of Recent Experiments

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1. What do we mean by “realism” in physics?
2. Local realism: The EPR-Bell setup
3. Three recent EPR-Bell experiments*
4. Macrorealism: The MQC Setup
5. A recent MQC experiment†

* B. Hensen et al., Nature 526, 682 (2015) (“Delft”)
L. K. Shalm et al. Phys. Rev. Letters 115, 250402 (2015) (“NIST”)
M. Giustina et al, Phys. Rev. Letters 115, 250401 (2015) (IQOQI”)

† G. C. Knee et al., arXiv: 1601.03728 (2016) (“NTT”)

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.

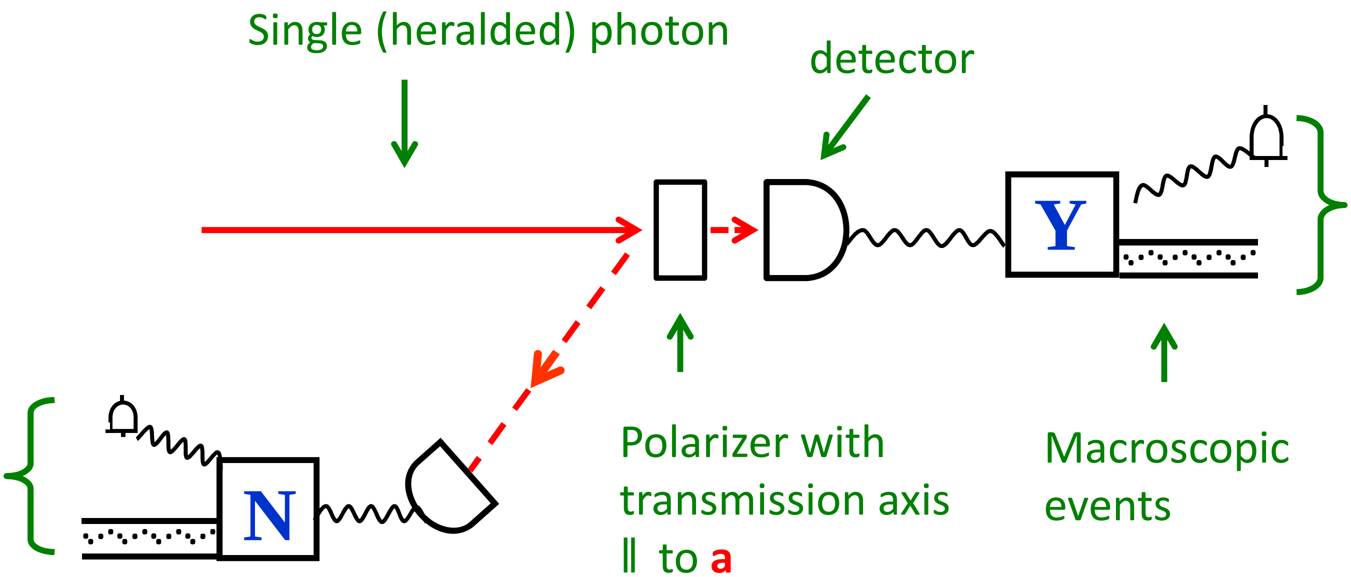
Irrespective of the universal validity (or not) of QM, what can we infer about this proposition

directly from experiment?

↑ quantum mechanics

THE SIMPLEST CASE: A TWO STATE SYSTEM

(Microscopic) example: photon polarization



"Question" posed to photon:

Are you polarized along **a**?

Experimental fact:

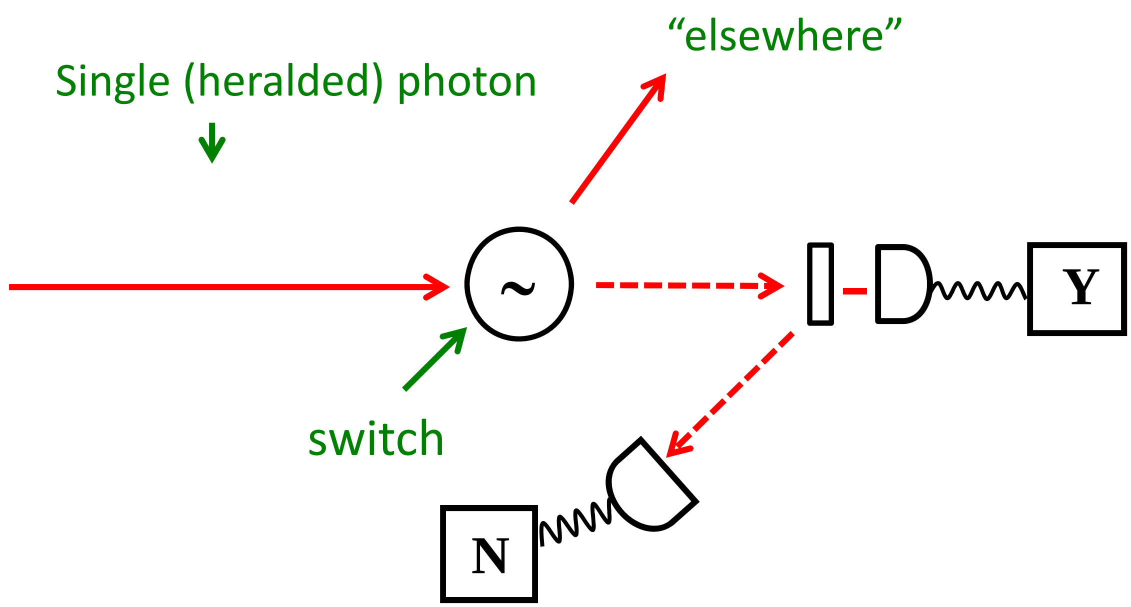
for each photon, either counter Y clicks (and counter N does not) or N clicks (and Y does not).

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…)



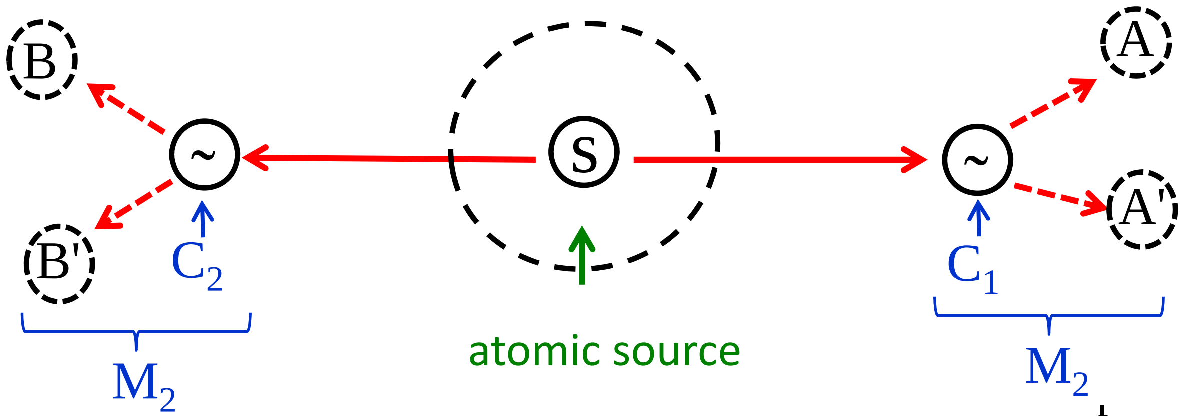
Suppose a given photon is directed "elsewhere".
What does it mean to ask "does it have a definite value of A?"?
A possible quasi-operational definition:
Suppose photon had been switched into measuring device:
Then:
Proposition I (truism?): It is a fact that either counter Y would have clicked (A = +1)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

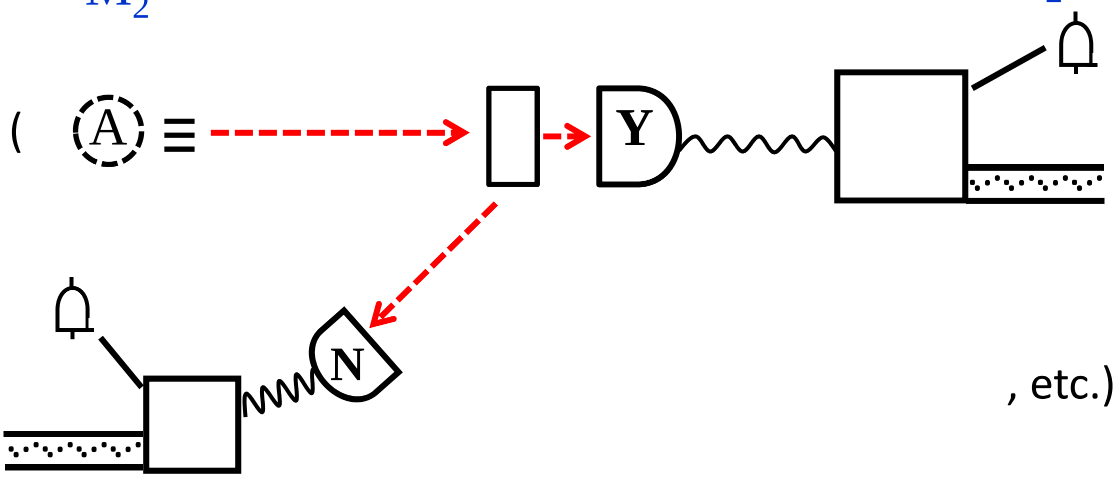
$\Downarrow$?

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)

DO COUNTERFACTUAL STATEMENTS HAVE TRUTH VALUES?
(common sense, legal system… assume so!)

THE EPR-BELL EXPERIMENTS (idealized)





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

$$\langle AB \rangle + \langle A'B \rangle + \langle AB' \rangle - \langle A'B' \rangle \leq 2 \qquad (*)$$

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

Note: for purposes of refuting local realism, use of "source" is inessential!

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.

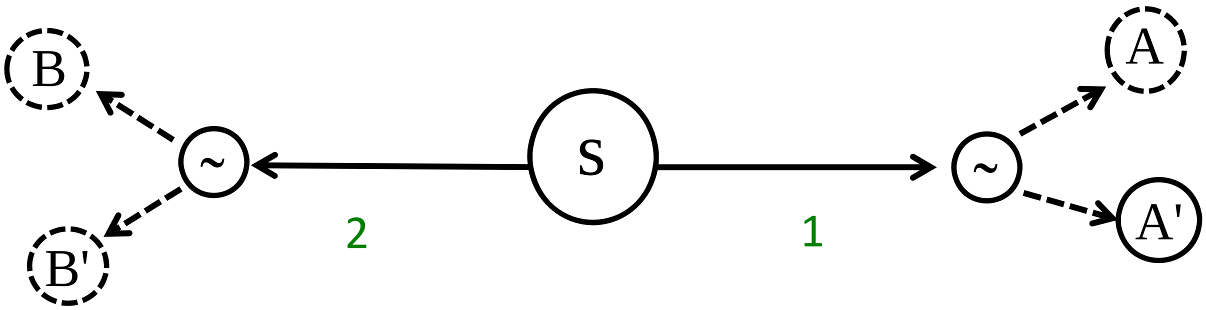
Why?

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

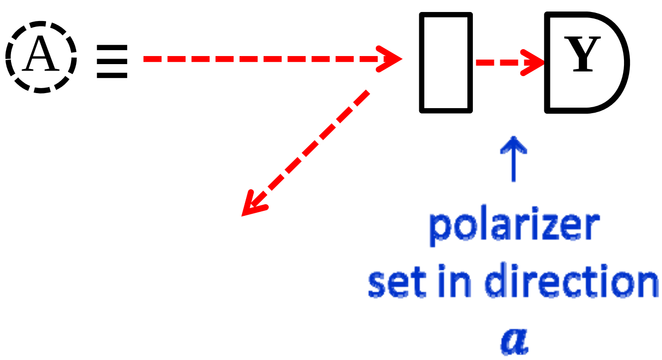
Blocking of (3) requires detector efficiency >82.8% for CHSH (or 67% for Eberhard, see below) — easy for atoms, etc., difficult for photons

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.)

(so don't mind whether nondetected particles had polarization ⊥ **a**, or were simply not detected because of inefficiency of counter).

Eberhard inequality:

$$J \equiv p(++|ab) - p(+0|ab') - p(0+|a'b) - p(++|a'b') \leq 0$$

where, e.g.,

$p(+0|ab) \equiv$ 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)/J	Significance
Delft	electron spins	1.3 km	CHSH	0.42	0.019/0.039
NIST	photon polarization	185m	Eberhard	2 x 10^{-7}	<2.3 x 10^{-3}
IQOQI	photon polarization	58m	Eberhard	7 x 10^{-7}	$<10^{-30}$[sic!]

⇒ local realism is dead?

What are the outstanding loopholes?

(1)Superdeterminism — probably untestable

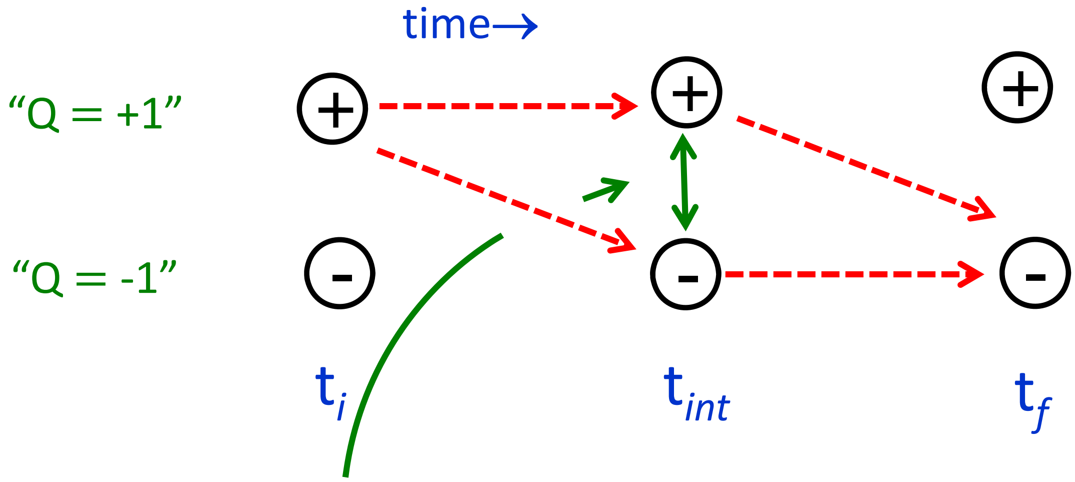
(2)retrocausality — probably untestable

(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":

Existing 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)

Analog of CHSH theorem for MQC:
Any macrorealistic theory satisfies constraint

$$-2 \leqslant \langle Q(t_1)Q(t_2)\rangle + \langle Q(t_2)\,Q(t_3)\rangle + \langle Q(t_3)Q(t_4)\rangle - \langle Q(t_1)Q(t_4)\rangle \leq 2$$

or setting $t_4 = t_1$,

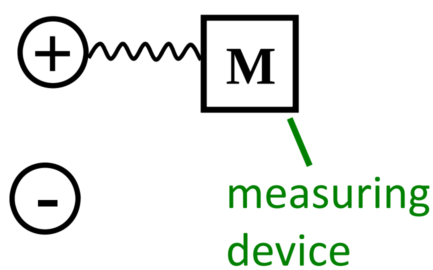
$$\langle Q(t_1)\,Q(t_1)\rangle + \langle Q(t_2)\,Q(t_3)\rangle + \langle Q(t_3)\,Q(t_1)\rangle \geqslant -1$$

which is violated (for appropriate choices of the t_i) by the QM predictions for an "ideal" 2-state system

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)

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").

Existing experiments use "weak-measurement" techniques (and states are not macroscopically distinct)

<u>NTT experiment</u>

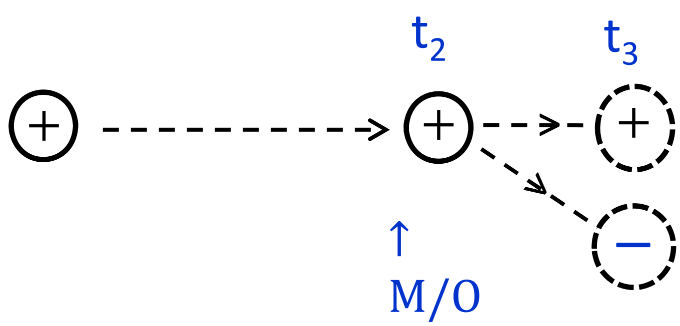
Rather than measuring 2-time correlations, check directly how far measurement (not necessarily noninvasive) at t_2 affects $\langle Q(t_3)\rangle \equiv \langle Q_3\rangle$ for the different macroscopically distinct states and for their (putative) quantum superposition.

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

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

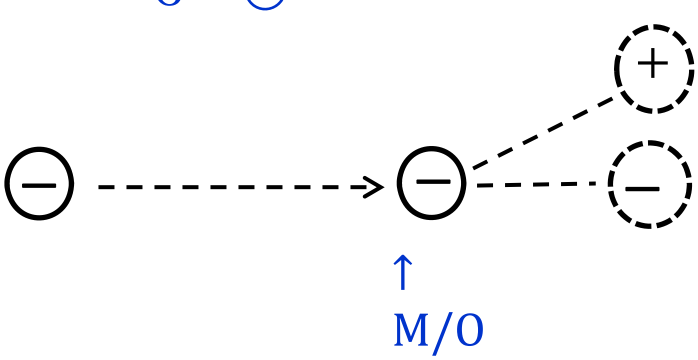
- $M \equiv$ measurement with uninspected outcome made at t_2
- $O \equiv$ measurement not made at t_2

Ancillary test: $\sigma = \oplus$



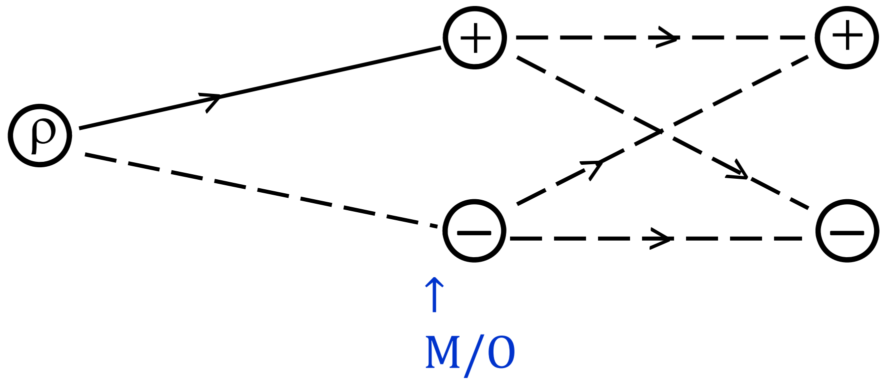
$$d_+ \equiv \langle Q_3\rangle_M - \langle Q_3\rangle_O$$

$\sigma = \ominus$



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

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!

CONCLUSION

Not just at the level of photons/electrons, but even at the level of superconducting qubits,

"unperformed experiments have no results"

or more generally

counterfactual statements have no truth-values.

(are the philosophers surprised?)