# The Structure of a World (which may be) Described by Quantum Mechanics

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Theoretical account of the world given by quantum mechanics (QM) is very bizarre.

But, a theory is only as good as the experiments which support it.

So:

What can we infer about the nature/structure of the physical world

(a) from existing experiments which test QM

(b) on the assumption that all future experiments will confirm predictions of QM?

Two major areas of experimentation:

1) EPR-Bell

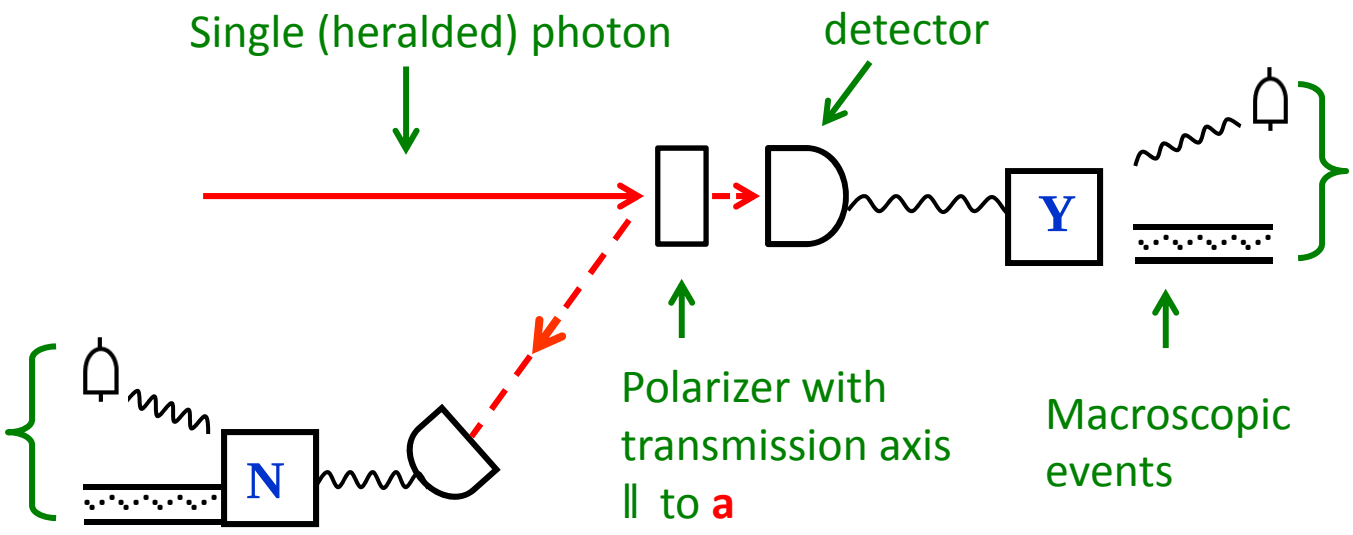
2) Schrödinger's cat

Both (may) involve in their interpretation the concept of realism.

So: what do we (can we) mean by "realism" in physics?

# "Realism" in the Simplest Case: A Two State System

(Microscopic) example: photon polarization




"Question" posed to photon:

Are you polarized along **a**? ("A = +1")

or perpendicular to **a**? ("A = -1")

Experimental fact:

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

natural "paraphrase":

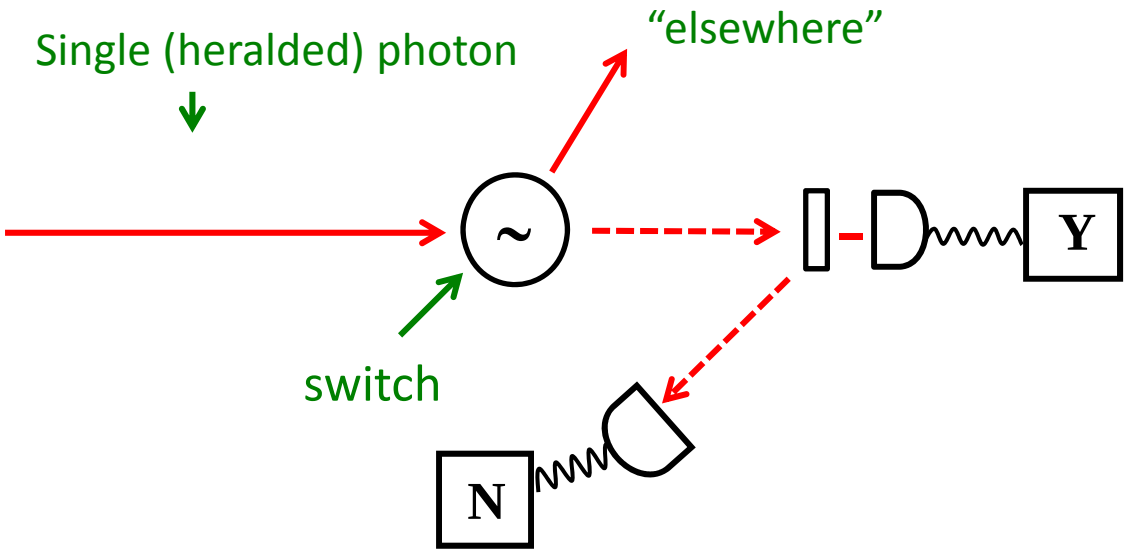
when asked, each photon answers either "yes" (A = +1) or "no" (A = -1)

But: what if it is not asked?

(no measuring device…)

Single (heralded) photon

# MACROSCOPIC COUNTERFACTUAL DEFINITENESS (MCFD)




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:

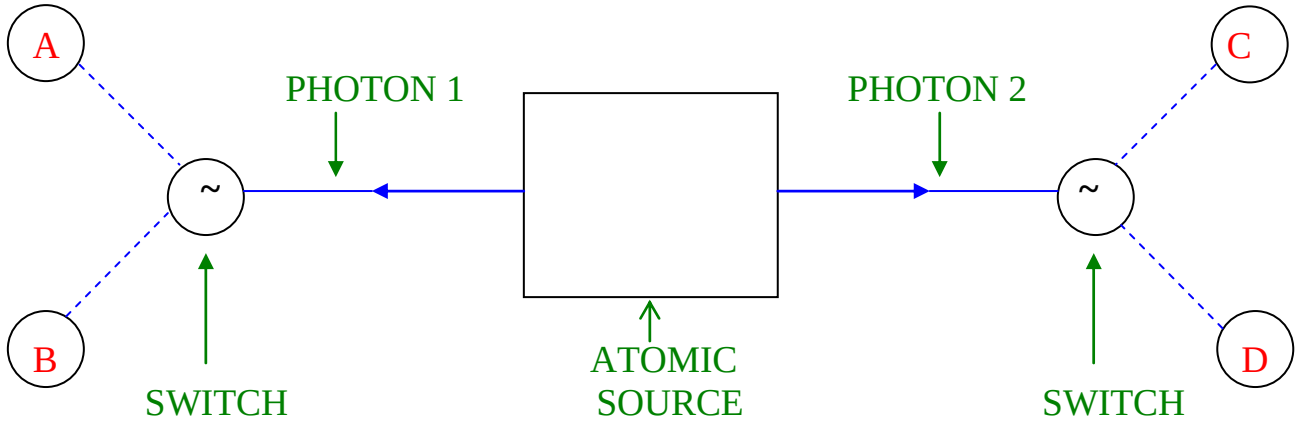
Proposition I (truism?): It is a fact that either counter Y would have clicked (A = +1) or counter N would have clicked (A = -1)

$\Downarrow$ ?

Proposition II (macroscopic counterfactual definiteness): 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)

Nb: Microrealism $\rightleftarrows$ MCFD

# EXPERIMENTS ON CORRELATED PHOTONS




(A ≡ , etc.)

transm. axis = $\underset{\sim}{a}$

DEFINITION: If photon 1 is switched into counter "A"

If counter "A" clicks, A = + 1 (DF.)

If counter "A" does not click, A = – 1 (DF.)

NOTE:

If photon 1 switched into counter "B", then A is NOT DEFINED.

Experiment can measure

$\langle AC \rangle_{exp}$ on one set of pairs (1→ "A", 2 → "C")

$\langle AD \rangle_{exp}$ on another set of pairs (1→ "A", 2→ "D")

etc.

Of special interest is

$$K_{exp} \equiv \langle AC \rangle_{exp} + \langle AD \rangle_{exp} + \langle BC \rangle_{exp} - \langle BD \rangle_{exp}$$

for which Q.M. makes clear predictions.

## POSTULATES OF "OBJECTIVE LOCAL" THEORY:

(1) Local causality
(2) Usual "arrow of time"
(3) Microscopic realism OR macroscopic

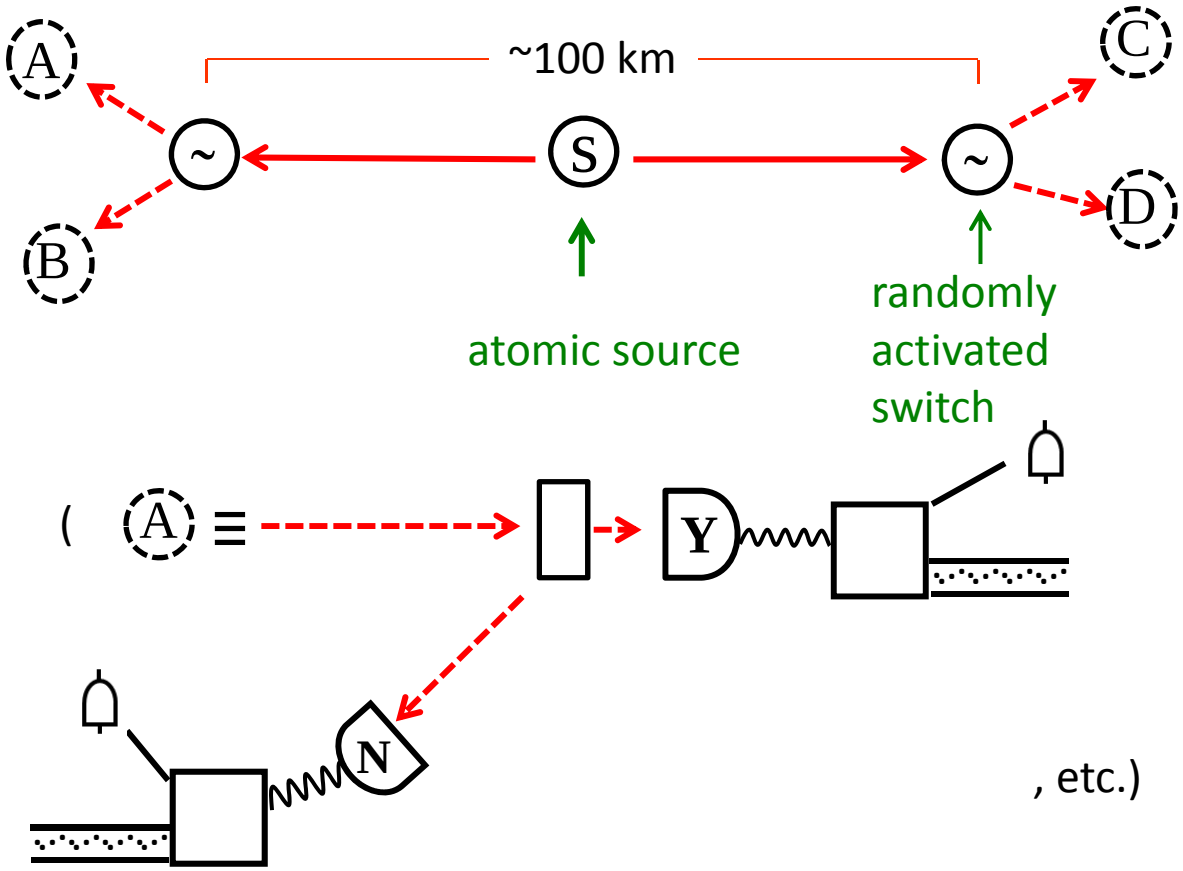
"counter-factual definiteness"

## "CHSH" THEOREM

1. (3) $\rightarrow$ For each photon 1, EITHER A = + 1 OR A = – 1, independently of whether or not A is actually measured.
2. (1) $\rightarrow$ Value of A for any particular photon 1 unaffected by whether C or D measured on corresponding photon 2.
   : etc.
3. $\therefore$ For each pair, quantities AC, AD, BC, BD exist, with A, B, C, D, = $\pm$ 1 and A the same in (AC, AD) (etc.)
4. Simple algebra then $\rightarrow$ for each pair,
   $AC + AD + BC - BD \leq 2$
5. Hence for a single ensemble,
   $\langle AC \rangle_{ens} + \langle AD \rangle_{ens} + \langle BC \rangle_{ens} - \langle BD \rangle_{ens} \leq 2$
6. (2) $\rightarrow \langle AC \rangle_{exp} = \langle AC \rangle_{ens}$, hence the measurable quantity
   $K_{exp} \equiv \langle AC \rangle_{exp} + \langle BC \rangle_{exp} + \langle BC \rangle_{exp} - \langle BD \rangle_{exp}$
   satisfies

$$K_{exp} \leq 2, \quad \text{Obj. Local Theory}$$

# THE EPR-BELL EXPERIMENTS (idealized)




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

$$\langle AC\rangle_{exp} + \langle AD\rangle_{exp} + \langle BC\rangle_{exp} - \langle BD\rangle_{exp} \leq 2 \qquad (*)$$

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

(↑: "loopholes" – individually blocked except for "collapse locality" loophole: at what point is a definite outcome "realized"?)

Thus, modulo "loopholes", all OLT's are refuted by experiment.

Defining postulates of an OLT: conjunction of

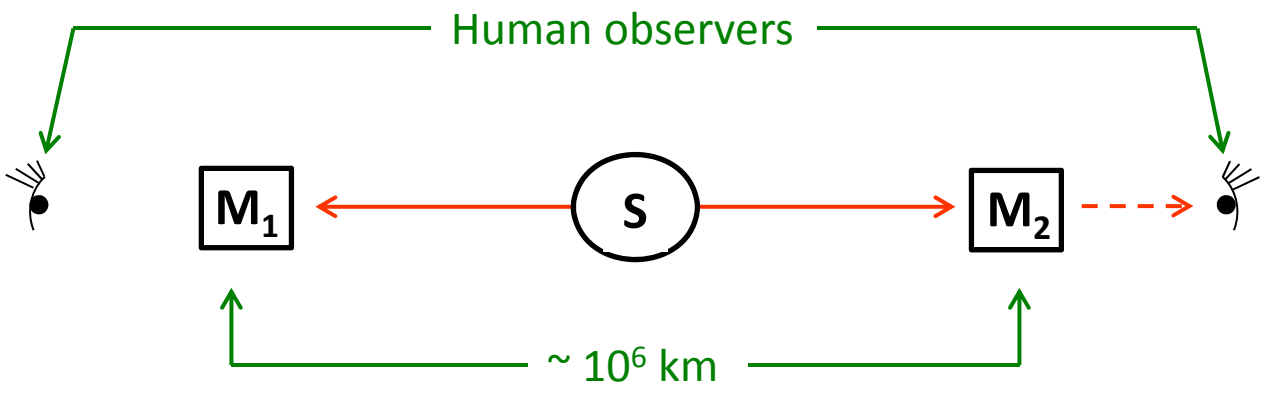
1) Standard "arrow of time"
2) Einstein locality (no superluminal causality)
3) Microrealism / MCFD

} Nb: (2)⇒(1) in SR but not necessarily in more general theory

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

↑: What about "collapse locality" loophole?

Maybe in future: long-baseline EPR-Bell experiment.

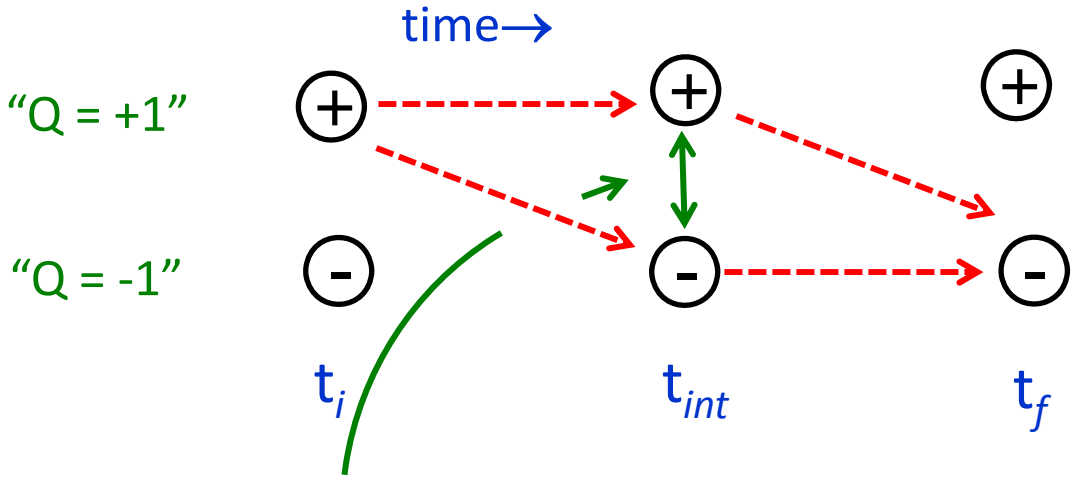



Until then, what can we say about the process (?) of "collapse" ("realization")?

Note existence of alternative (non-QM) scenarios (CSL, Penrose…)

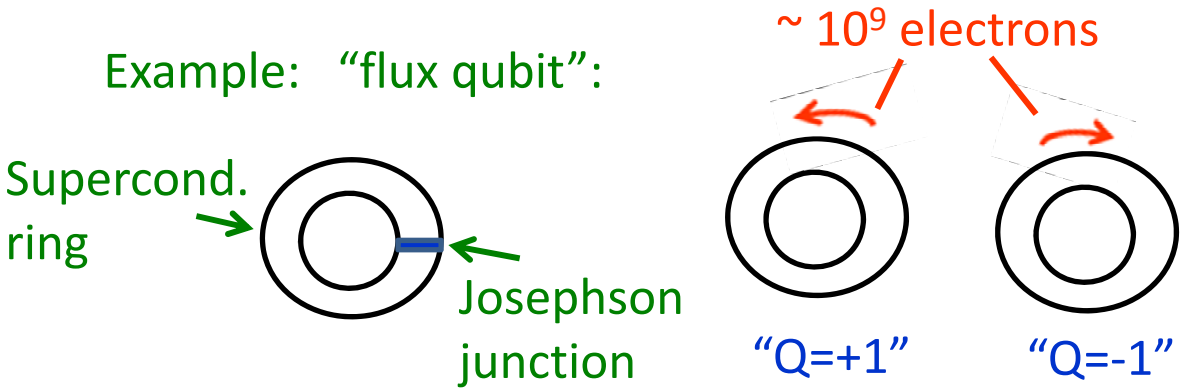
⇒ Can we build Schrödinger's Cat in the lab.?

# BUILDING SCHRÖDINGER'S CAT IN THE LAB: 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?

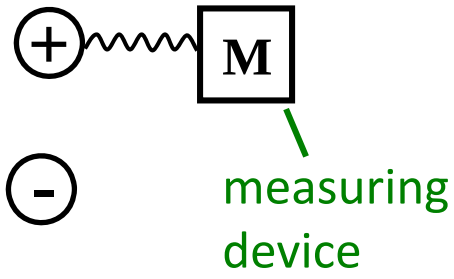
Analog of CHSH theorem for MQC:
Any macrorealistic theory satisfies constraint

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

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

Definition of "macrorealistic" theory: conjunction of
1) arrow of time
2) macrorealism (Q(t) = +1 or -1 for all t)
3) noninvasive measurability (NIM)

NIM:




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

In this case, unnatural to assert 3) while denying 2).
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 noninvasive measurement does or does not affect subsequent statistics. But measurements must be projective ("von Neumann").

Existing experiments use "weak-measurement" techniques (and arguable whether states macroscopically distinct)

# CONCLUSIONS

1. From existing EPR-Bell experiments, must either
   (a) reject at least one of
   - arrow of time
   - locality
   - MCFD ← macroscopic counterfactual definiteness

   or (b) invoke collapse locality loophole

2. If future long-baseline experiment verifies QM predictions,
   (b) is unviable.

3. If a future "proper" MQC experiment verifies QM predictions, must reject at least one of
   - arrow of time
   - macrorealism
   - NIM ← non-invasive measurability

4. If result of (3) is QM'ℓ but that of (2) not, raises question:
   are human "observers" special?

(Wigner's friend: UIUC experiment)

A final thought: is induction ("arrow of time") sacred?