

The Structure of a World 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

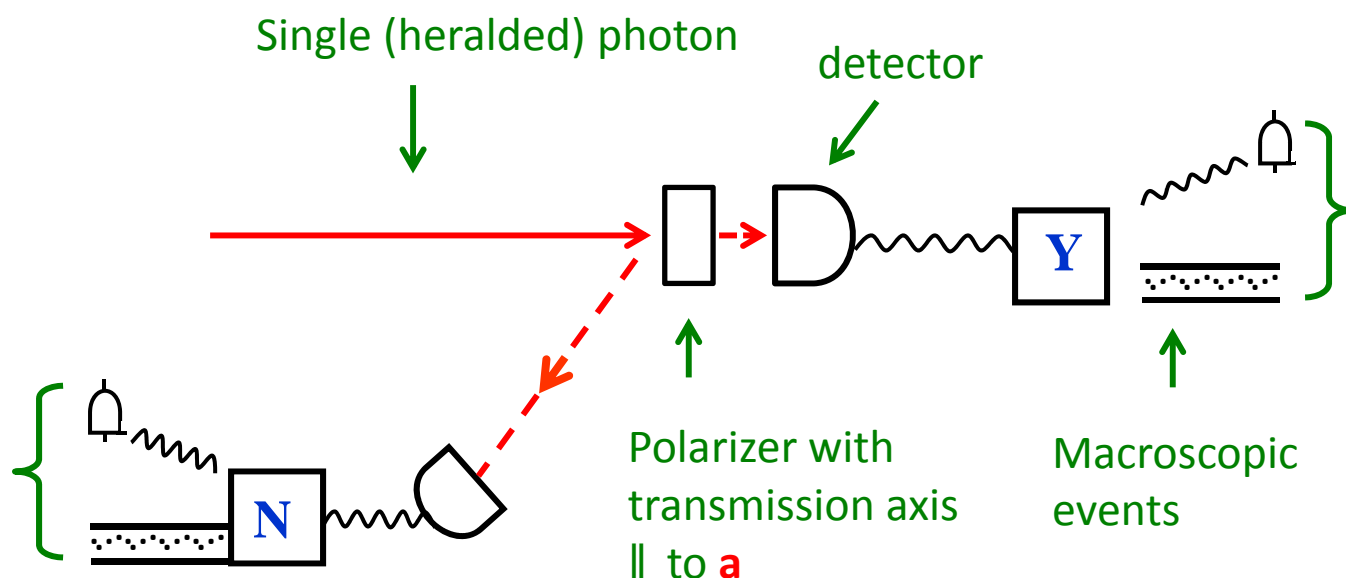
2) Schrödinger's cat

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).

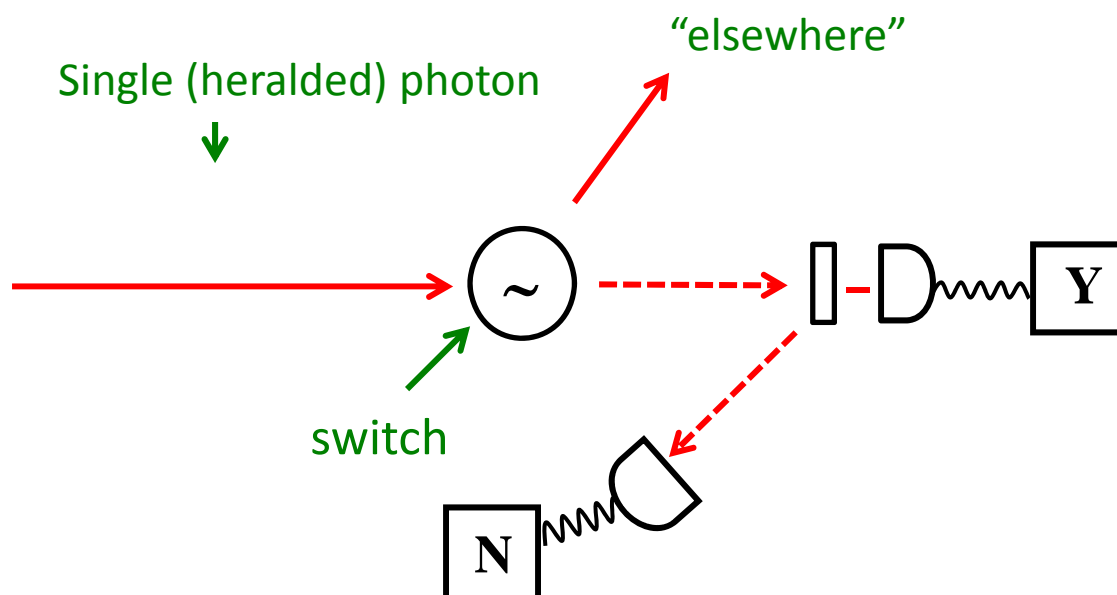
natural “paraphrase”:

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

But: what if it is **not** asked?

Single (heralded) photon \rightarrow (no measuring device...)

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 ($A = -1$)

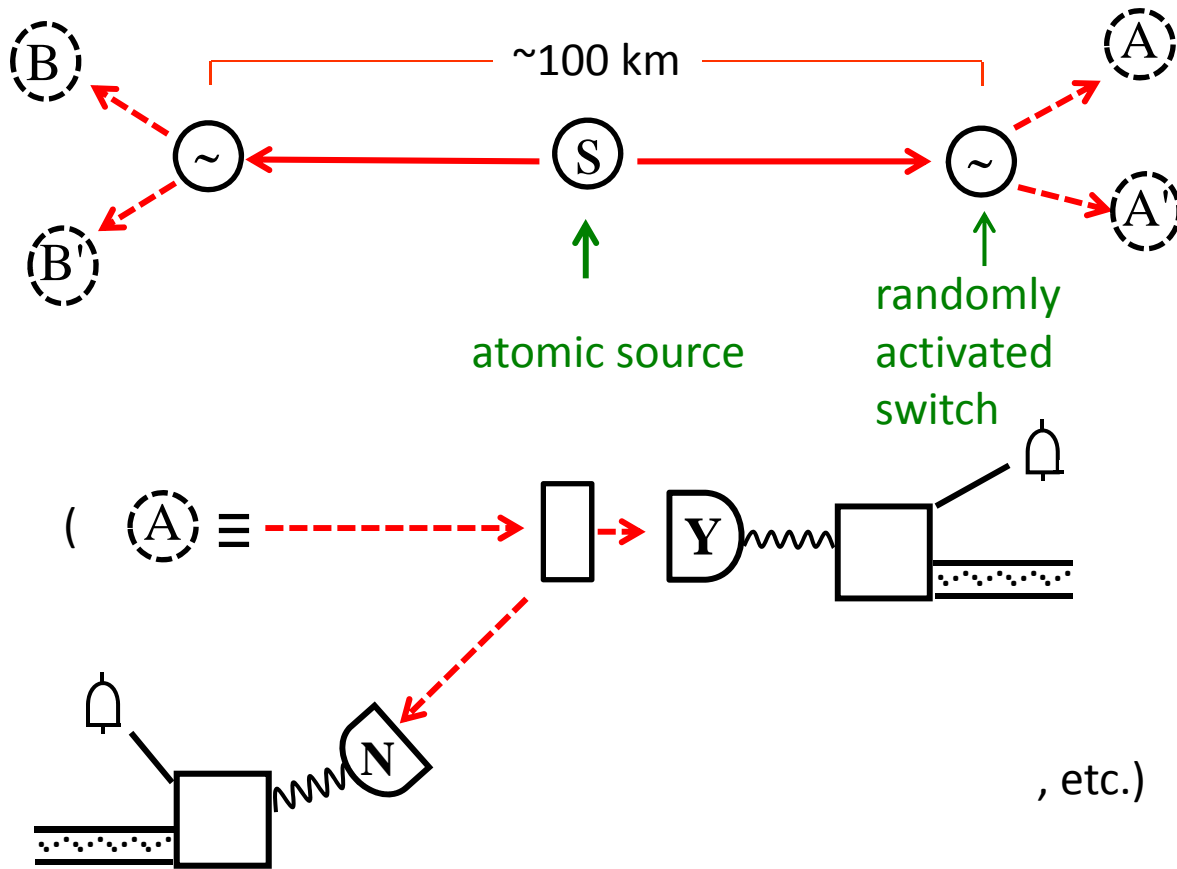


Proposition II (MCFD): **Either** it is a fact that counter Y would have clicked (i.e. it is a fact that $A = +1$) **or** it is a fact that counter N would have clicked ($A = -1$)

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

Microrealism \Rightarrow MCFD
 \nLeftarrow

THE EPR-BELL EXPERIMENTS (idealized)



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

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

(*) 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

- | | | |
|--|---|--|
| <ul style="list-style-type: none"> 1) Induction (\cong standard “arrow of time”) 2) Einstein locality (no superluminal causality) 3) Microrealism / MCFD | } | <p>Nb: (2)\Rightarrow(1) in SR
but not necessarily
in more general
theory</p> |
|--|---|--|

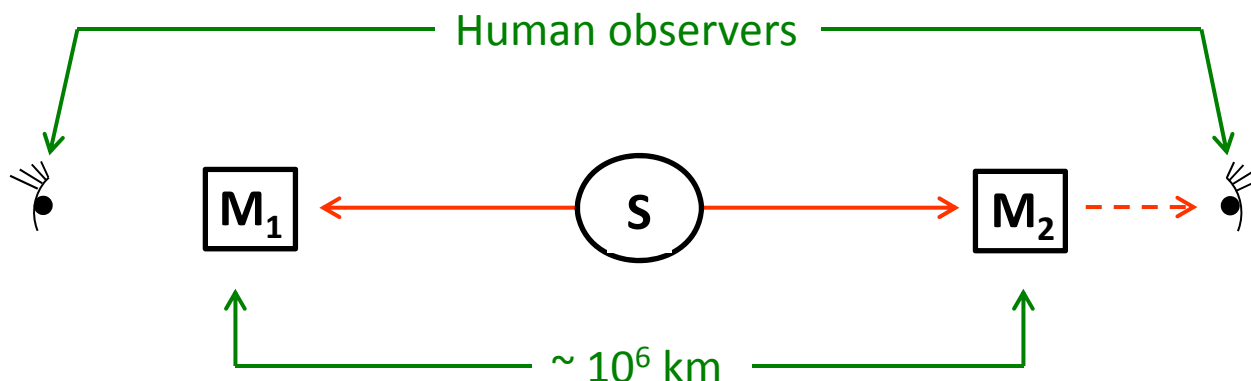
Can we do without (3)? (i.e. are (1) and (2) alone sufficient to prove CHSH theorem?)

Involves v. delicate questions concerning definition of probability...

Anyway, irrespective of this, existing experiments *prima facie* imply at least one of (1) – (3) has to go.

↑: What about “collapse locality” loophole?

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

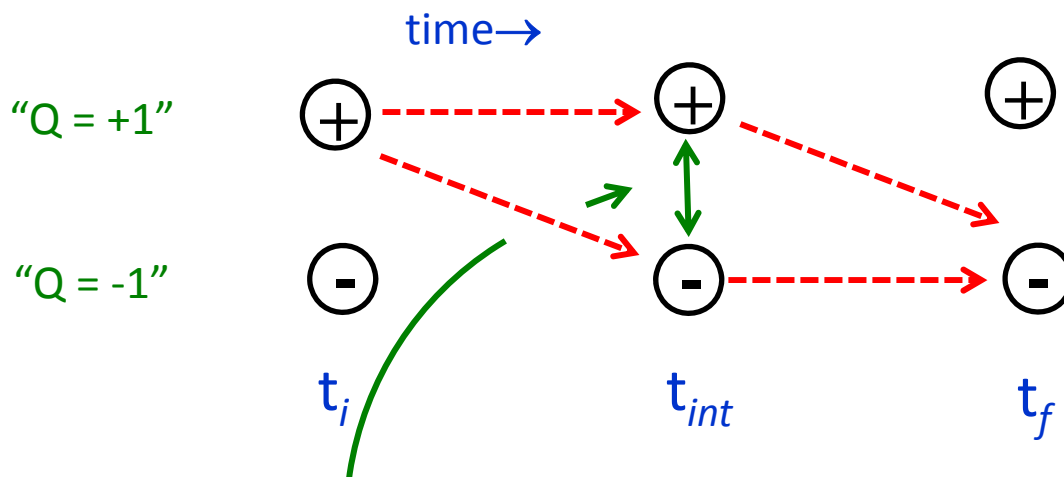


Until then, what can we say about the process (?) of “collapse” (“realization”)?

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

\Rightarrow Can we build 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 \oplus and \ominus .

↑: how “macroscopically” distinct?

Analog of CHSH theorem for MQC:

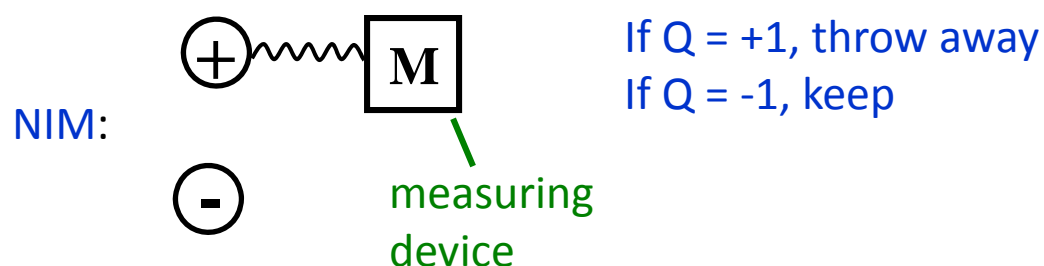
Any **macrorealistic** theory satisfies constraint

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

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

Definition of “macrorealistic” theory: conjunction of

- 1) induction
- 2) macrorealism ($Q(t) = +1$ or -1 for all t)
- 3) noninvasive measurability (NIM)



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
 - { induction
 - { 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 MQC experiment with v.N. measurements verifies QM predictions, must reject at least one of
 - { induction
 - { 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?**