# Why I Don't Believe that Quantum Mechanics is the Whole Truth

Anthony J. Leggett

University of Illinois at Urbana-Champaign

Current interest in [questions regarding the quantum measurement problem] is small. The typical physicist feels that they have long been answered, and that he will fully understand just how if ever he can spare twenty minutes to think about it.

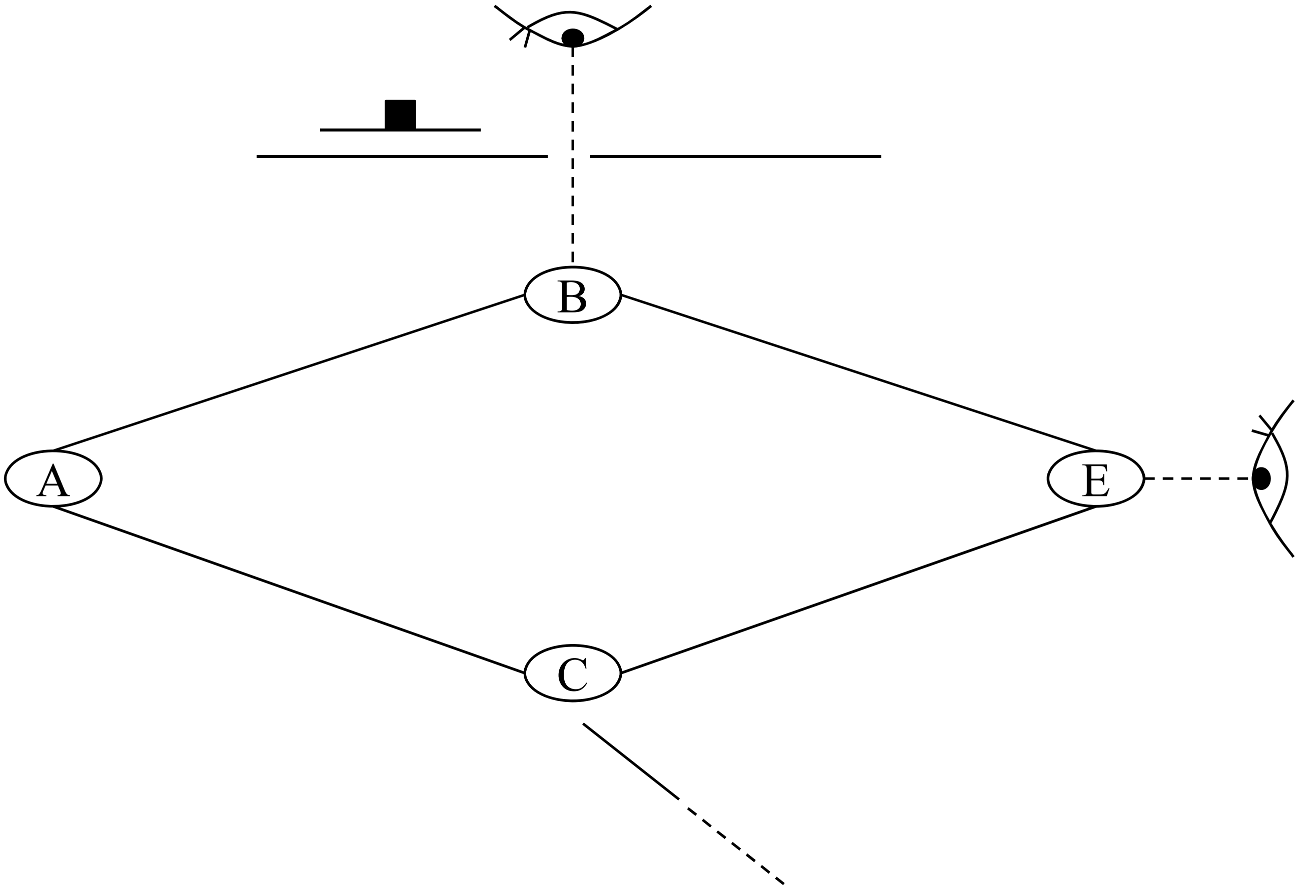
J. S. Bell and M. Nauenberg, 1966

The problem of measurement in quantum mechanics is considered as nonexistent or trivial by an impressive body of theoretical physicists and as presenting almost insurmountable difficulties by a somewhat lesser but steadily growing number of their colleagues.

B. d'Espagnat, 1971

And half a century, dozens of books and thousands of papers later…

# Basic "experimental fact"




## Experiment:

1. Shut off C, measure Prob. (A→B →E) (≡ "$P_B$")

2. Shut off B, measure Prob. (A→C →E) (≡ "$P_C$")

3. Open both paths, measure Prob. $\left(A \rightarrow \begin{Bmatrix} B \\ C \end{Bmatrix} \rightarrow E\right)$ (≡ $P_{BorC}$")

Result:

A. Look to see whether path B or C is followed:

a) Every individual atom (etc.) follows either B or C.

b) $P_{\text{B or C}} = P_B + P_C$ ("common sense" result)

B. Don't look:

$$P_{\text{B or C}} \neq P_B + P_C$$

In fact, can have:

$$P_B \neq 0,\ P_C \neq 0, \text{ but } P_{\text{B or C}} = 0!$$

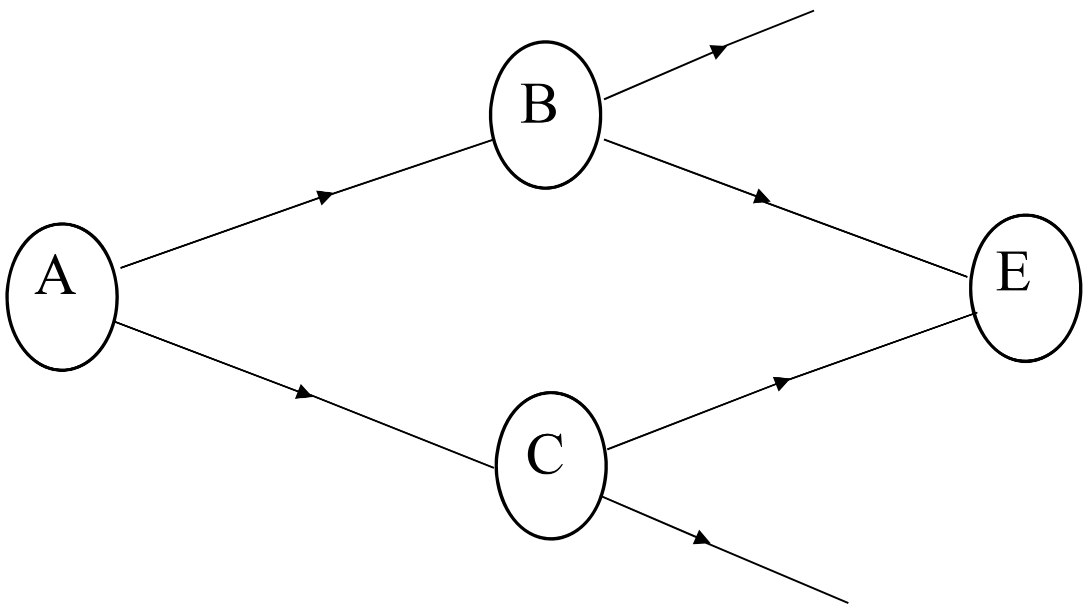
What we might say:

- each atom passes through both B and C
- each atom passes through neither B nor C
- the question of which path is followed by a given atom is meaningless

- But one thing we apparently cannot say is that each atom either passes through B or passes through C.

(Vote)

# Account given by quantum mechanics:




Each possible process is represented by a probability amplitude A which can be positive or negative

- Total amplitude to go from A to E sum of amplitudes for possible paths, i.e. A→B→E and/or A→C→E

- Probability to go from A to E = square of total amplitude

1. If C shut off: $A_{tot} = A_B \Rightarrow P \equiv P_B = A_B^2$

2. If B shut off: $A_{tot} = A_C \Rightarrow P \equiv P_C = A_C^2$

3. If both paths open:

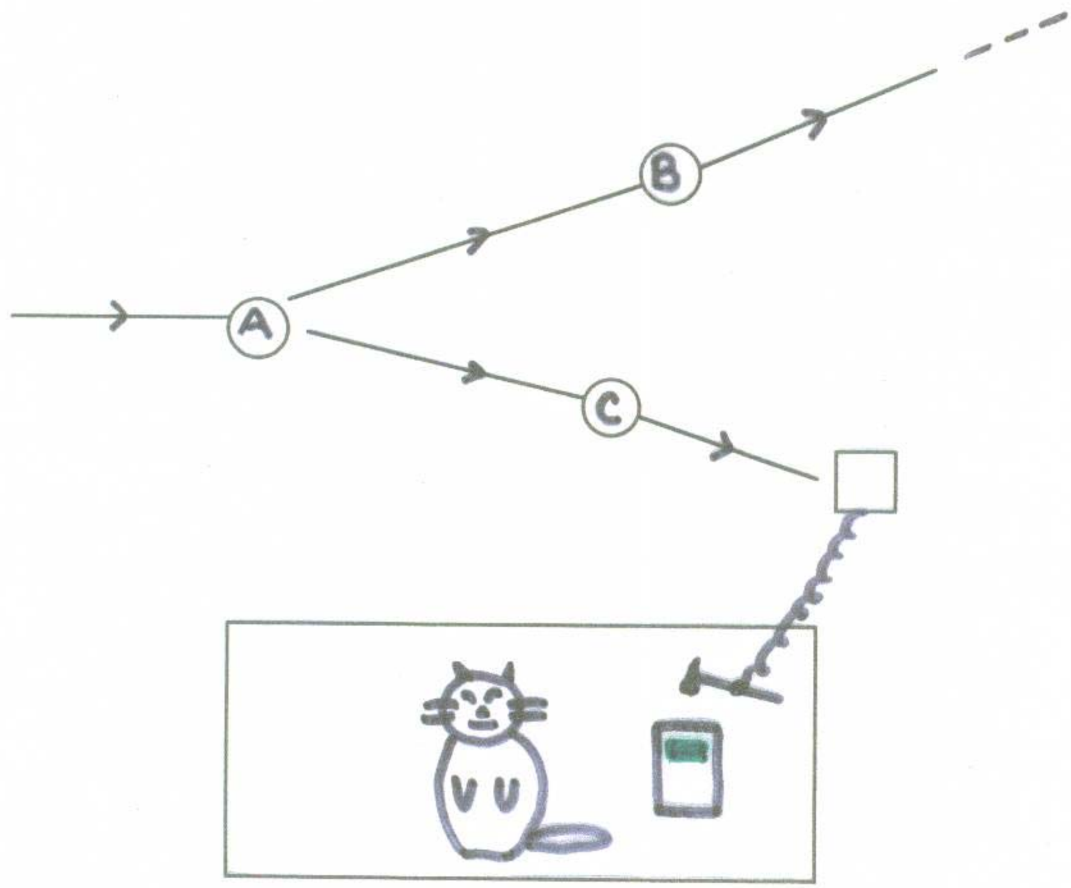
$A_{tot} = A_B + A_C$ ← "SUPERPOSITION"

$\Rightarrow P \equiv P_{B\text{ or }C} = A_{tot}^2 = (A_B + A_C)^2 = A_B^2 + A_C^2 + 2\,A_B\,A_C$

$\Rightarrow P_{B\text{ or }C} = P_B + P_C + 2A_BA_C$

↑ "interference" term

To get interference, $A_B$ and $A_C$ must simultaneously "exist" for each atom. Conversely, whenever $A_B$ and $A_C$ are simultaneously nonzero, get interference $\Rightarrow$ neither B nor C selected by each atom.




In quantum mechanics, if state 1 → state 1' and state 2 → 2' , then <u>superposition</u> of 1and 2 → superposition of 1' and 2'.

Here, B → cat alive
C → cat dead

∴ Superposition of B and C
→ <u>superposition of “alive” and “dead”!</u>

i.e.

$$\begin{cases} \text{ampl. (cat alive)} \neq 0 \\ \text{ampl. (cat dead)} \neq 0 \end{cases}$$

So: is it true that each individual cat of the ensemble, before we inspect her, either is alive or is dead?
(Vote)

## SOME ALLEGED "SOLUTIONS" OF THE QUANTUM MEASUREMENT PROBLEM (under the assumption that QM is the complete truth about the physical worlds, at both the microscopic (μ) and macroscopic (M) level)

Classify by answers to the question: Do QM amplitudes correspond to anything "out there"?

| Interpretation | μ level | M level |
|---|---|---|
| Statistical | no | no |
| Relative-state ("many-worlds") | yes | yes |
| Orthodox ("decoherence") | yes | no |

# THE DECOHERENCE ARGUMENT

Isolated system:

$$\psi = \alpha\psi_1 + \beta\psi_2 \qquad \left(\hat{\rho} = \begin{pmatrix} |\alpha|^2 & \alpha\beta^* \\ \alpha^*\beta & |\beta|^2 \end{pmatrix}\right)$$

consider operator $\langle\hat{\Omega}\rangle$ which acts only on system:

expectation value $\langle\hat{\Omega}\rangle$ given by

$$\langle\hat{\Omega}\rangle = \langle\psi|\hat{\Omega}|\psi\rangle = Tr\hat{\rho}\hat{\Omega} =$$

$$|\alpha|^2\Omega_{11} + |\beta|^2\Omega_{22} + 2Re(\Omega_{12}\alpha\beta^*)$$

Now couple to environment E:

(a) E classical (large-amplitude coherent state, e.g. "passing truck", 50 Hz background): ("classical noise"):
For particular instantiation *i* of noise:

$$\psi_i = (\exp i\delta)\alpha\psi_1 + (\exp i\,\epsilon)\beta\psi_2$$

↑ random phases ↑

$$\Longrightarrow \langle\Omega\rangle_i = |\alpha|^2\Omega_{11} + |\beta|^2\Omega_{22} + 2Re(\Omega_{12}\alpha\beta^* \exp i(\delta - \epsilon))$$

and when averaged over instantiations,

$$\left(\overline{\exp i(\delta - \epsilon)} = 0\right)$$

$$(\hat{\rho}_S)_{\text{av}} = \begin{pmatrix} |\alpha|^2 & 0 \\ 0 & \beta^2 \end{pmatrix} \qquad \langle\Omega\rangle_{\text{av}} = |\alpha|^2\Omega_{11} + |\beta|^2\Omega_{22}$$

(b) E quantum:

$$\Psi_{\mathrm{SE}}^{(0)} = (\alpha\psi_1 + \beta\psi_2)\chi_0 \qquad (\hat{\rho}_S) = \begin{pmatrix} |\alpha|^2 & a\beta^* \\ \alpha^*\beta & |\beta|^2 \end{pmatrix}$$

↑ state of E

$$\Longrightarrow (\alpha\psi_1\chi_1 + \beta\psi_2\chi_2) \qquad (\hat{\rho}_S) = Tr_E\hat{\rho}_{SE} = \begin{pmatrix} |\alpha|^2 & 0 \\ 0 & |\beta|^2 \end{pmatrix}$$

↑ orthogonal ↑
states of E

entanglement!

$$\langle\hat{\Omega}\rangle = |\alpha|^2\Omega_{11} + |\beta|^2\Omega_{22}$$

which is exactly the value for a system S in classical mixture of 1 and 2 with probability $|\alpha|^2$, $|\beta|^2$.

Decoherence expected to increase as transit from μ to M.

Claim of decoherence argument:

After a sufficient amount of decoherence, system really is in state 1(2) with probability $|\alpha|^2$, $|\beta|^2$.

What is wrong with this argument?

Answer: Nothing in the QM formalism has changed!

-- for classical environment, ensemble is a mixture of sub ensembles *i* in which amplitudes for 1 and 2 are each nonzero

-- for quantum environment, amplitudes for $|1\rangle|\chi_1\rangle$ and $|2\rangle|\chi_2\rangle$ are each nonzero.

At microlevel, we concluded that when amplitudes for $|1\rangle$ and $|2\rangle$ are both nonzero, we cannot say that each system of the ensemble is either in $|1\rangle$ or in $|2\rangle$. This is a statement about the meaning of the quantum formalism: the evidence that it is correct is the experimental data on interference.

At the macrolevel, (we all agree that) evidence has gone away: but nothing in the quantum formalism is changed!

The crucial question:

Does the vanishing of the evidence against a particular interpretation of the meaning of the quantum formalism entitle us to re-introduce this meaning?

(Murder-trial analogy…)

---

So, what about (a) statistical and (b) "many-worlds" interpretations?

Well, if we don't like any of the advertised solutions, what if we…

Assume quantum mechanics breaks down at some point en route from the atom to the cat

e.g. GRWP* theory

- universal, non-quantum mechanical "noise" background

- induces continuous, stochastic evolution to one or the other of 2 states of superposition

- trigger: "large" ($\gtrsim 10^{-5}$cm) separation of center of mass of N particles in 2 states

- rate of evolution $\propto$ N

- in typical "measurement" situations, all statistical predictions identical to those of standard quantum mechanics

also, theories based (e.g.) on special effects of gravity (Penrose, ...)

"macrorealism"

Objection: insensitivity of quantum formalism to scale, complexity…

---

*Ghirardi, Rimini, Weber , Pearle

Is quantum mechanics the whole truth?
How do we tell?
If all "everyday-scale" bodies have the property that the interference term is randomized ("decoherence"), always get "common sense" result, i.e. all experimental results will be "as if" one path or the other were followed.

⇒ cannot tell.
So: must find "everyday-scale" object where decoherence is not effective. Does any such exist?

Essential:
- difference of two states is at "everyday" level
- nevertheless, relevant energies at "atomic" level
- extreme degree of isolation from outside world
- very low intrinsic dissipation

QM CALCULATIONS HARD!

BASE ON:

a) A PRIORI "MICROSCOPIC" DESCRIPTION ✘

b) EXPTL. BEHAVIOR IN "CLASSICAL" LIMIT ✓

# WHY HAS (MUCH OF) THE QUANTUM MEASUREMENT LITERATURE SEVERELY OVERESTIMATED DECOHERENCE?

("electron-on-Sirius" argument: $\Delta\in \sim a^{-N} \sim \exp - N \leftarrow \sim 10^{23}$

$\Rightarrow$ Just about any perturbation $\gg \Delta\in \Rightarrow$ decoherence)

1. Matrix elements of S-E interaction couple only a very restricted set of levels of S.

2. "Adiabatic" ("false") decoherence:
   Ex.: spin-boson model

$$\hat{H} = \hat{H}_s + \hat{H}_E + \hat{H}_{S-E}$$

$$\hat{H}_s = \Delta\sigma_x$$

$\hat{H}_E =$ set of SHO's with lower frequency cutoff $\omega_{\min} \gg \Delta$

$\hat{H}_{S-E} = \hat{\sigma}_z \sum_\alpha C_\alpha \hat{x}_\alpha \leftarrow$ oscillator coords.

$\Psi_{\text{un}}(t=0) = |+>|\chi_+\rangle \leftarrow$ displaced state of oscillation

$$\hat{\rho}_s(t=0) = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \text{ (trivially)}$$

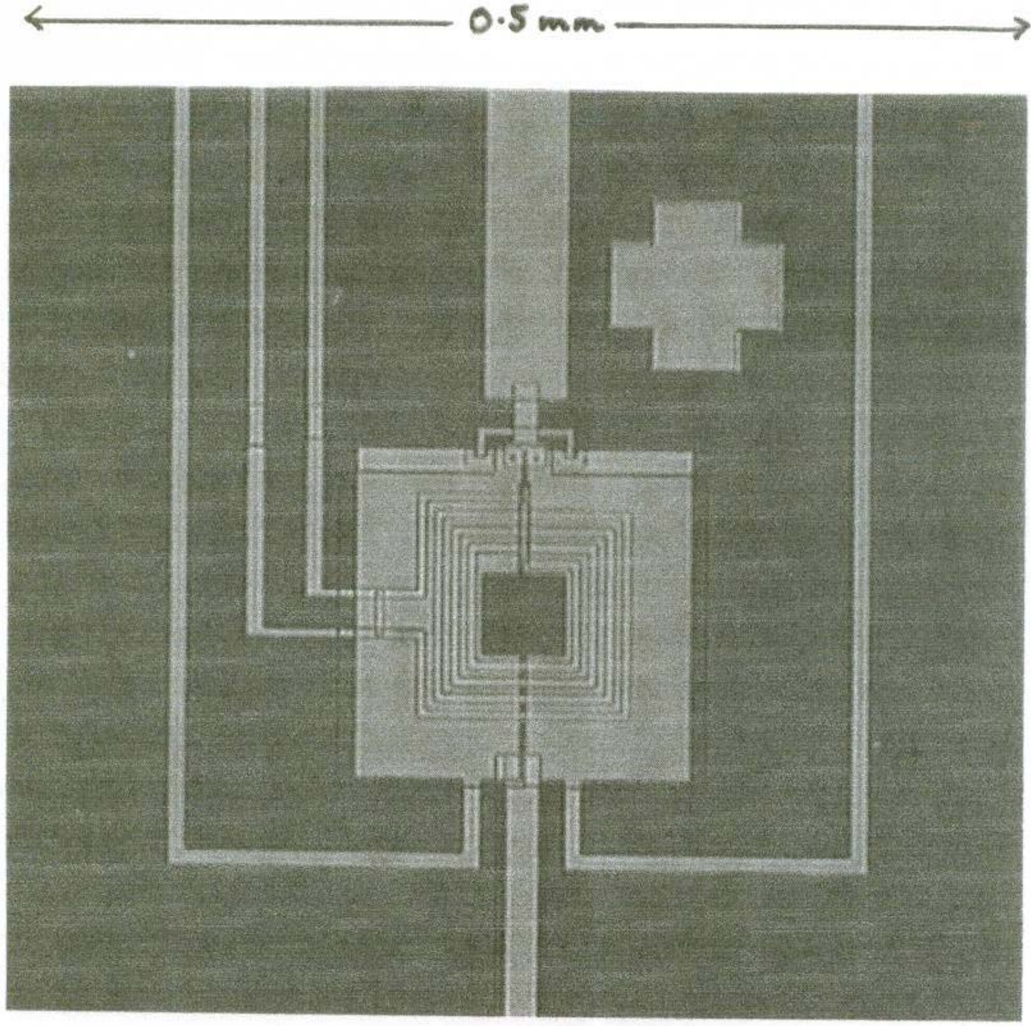
$$\Downarrow$$

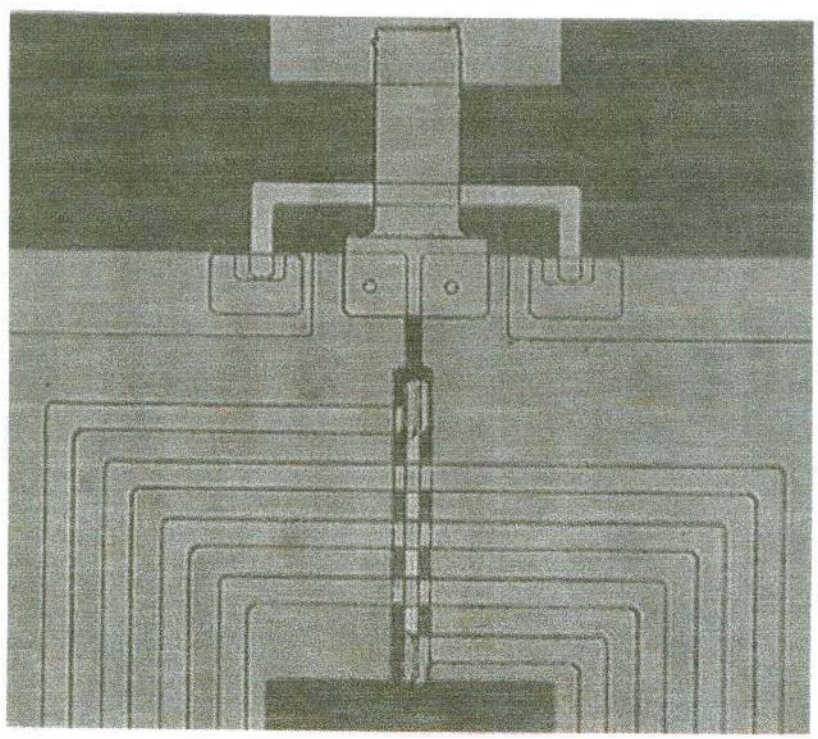
$$\Psi_{\text{un}}(t \sim \hbar/\Delta_{\text{un}}) \cong \frac{1}{\sqrt{2}}(|+>|\chi_+ > + |->|\chi_- >),$$

$$\langle \chi_+ | \chi_- \rangle = \exp - F \cong 0 \qquad \text{FC factor}$$

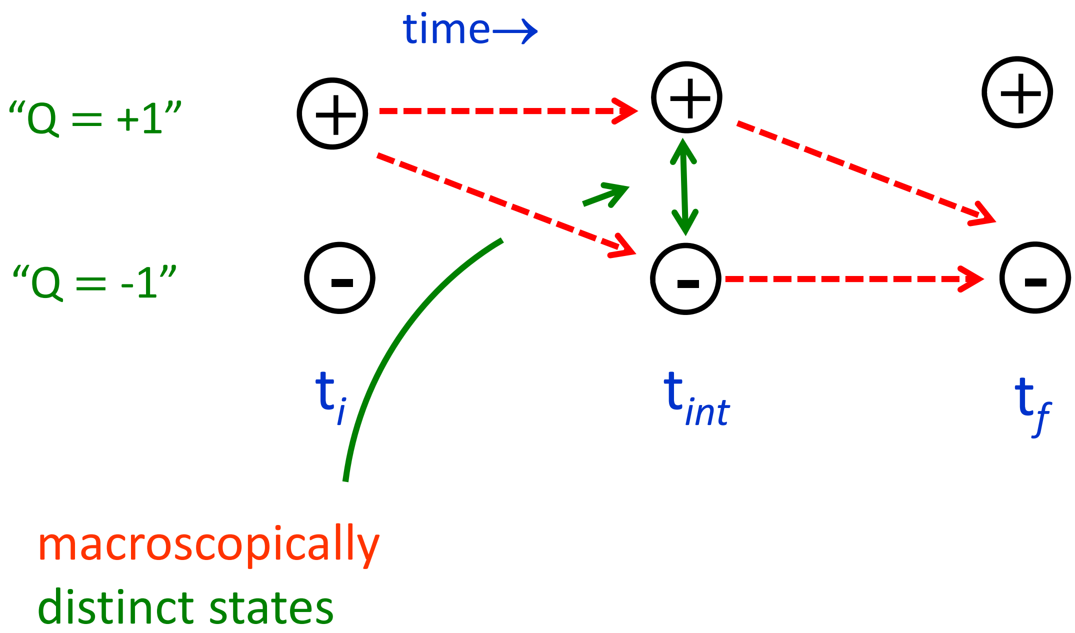
$$\Rightarrow \qquad \hat{\rho}_s(t \sim \hbar/\Delta_{nn}) \cong \begin{pmatrix} \frac{1}{2} & 0 \\ 0 & \frac{1}{2} \end{pmatrix}$$

decohered?? (cf. neutron interferometer)

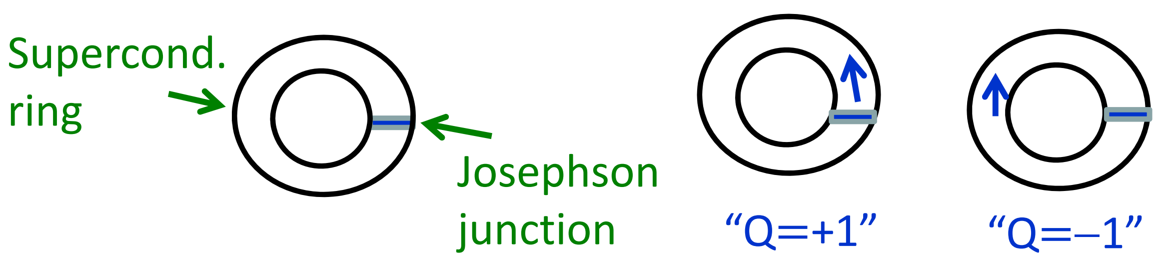

0·5 mm



# MACROSCOPIC QUANTUM COHERENCE (MQC)




Example: "flux qubit":




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

Analog of CHSH theorem for MQC ("temporal Bell inequality")*

Any macrorealistic theory satisfies constraint

$$-2 \leqslant \langle Q(t_1)Q(t_2)\rangle_{exp} + \langle Q(t_2)\, Q(t_3)\rangle_{exp} + \langle Q(t_3)Q(t_4)\rangle_{exp} - \langle Q(t_1)Q(t_4)\rangle_{exp} \leq 2$$

or setting (e.g.) $t_4 = t_1$ ,

$$\langle Q(t_1)\, Q(t_2)\rangle_{exp} + \langle Q(t_2)\, Q(t_3)\rangle_{exp} + \langle Q(t_3)\, Q(t_1)\rangle_{exp} \geqslant -1$$

(and similar) (Note: correlations $\langle Q(t_i)Q(t_j)\rangle$ for different i and/or j must be measured on different runs.)

which is violated (for appropriate choices of the $t_i$) by the QM predictions for an "ideal" 2-state system (e.g. $t_1 = 0$, $t_2 = 2\pi/3$, $t_3 = 4\pi/3$)

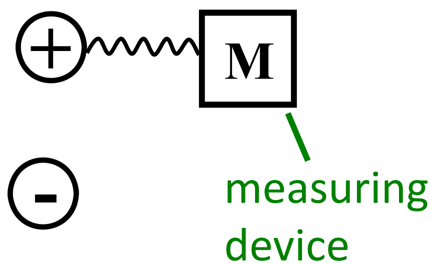
*AJL and Anupam Garg, PRL **54**, 857, (1985) Definition of "macrorealistic" theory: conjunction of

1) macrorealism "per se" ($Q(t) = +1$ or $-1$ for all t, whether observed or not)

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-2016 experiments use a "weak-measurement" techniques (and states were 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.

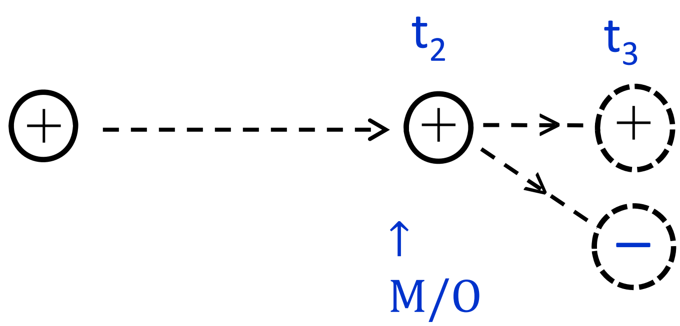
Define for any state $\sigma$ at $t=t_2-$,

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

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

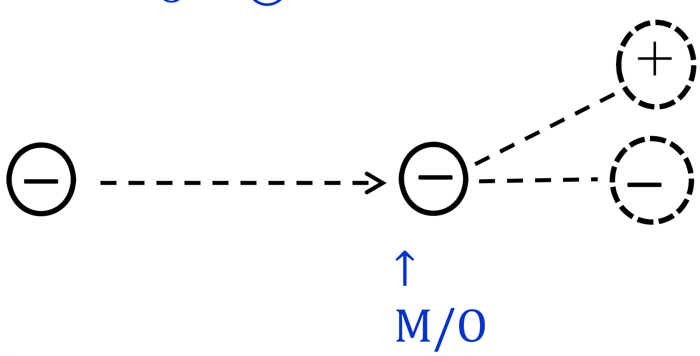
$O \equiv$ measurement not made at $t_2$

Ancillary test: $\sigma = \oplus$



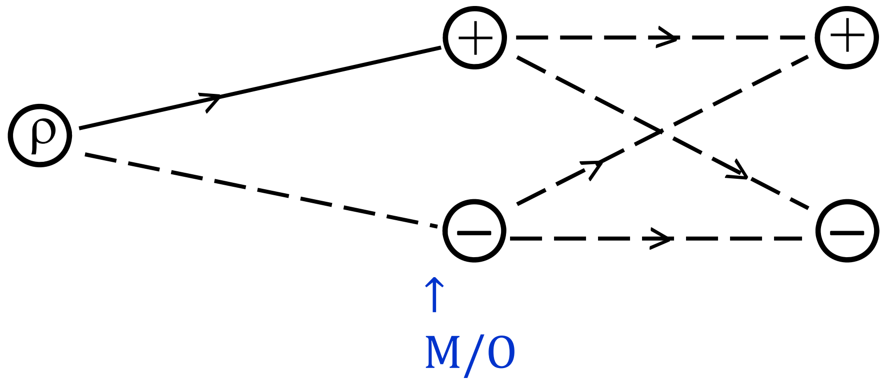

$$d_+ \equiv \langle Q_3\rangle_M - \langle Q_3\rangle_O$$

$\sigma = \ominus$




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

Main experiment:




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

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

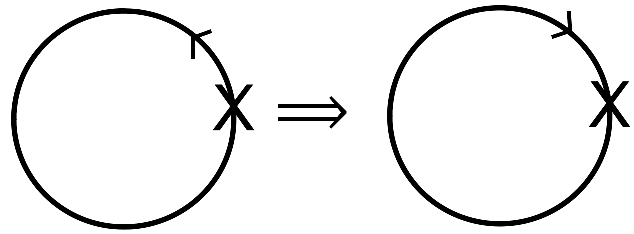
MR: $\delta > 0$

Expt: $\delta = -0.063$

violates MR prediction by > 84 standard deviations!

How "macroscopically distinct" are putatively superposed states of flux qubit?

Korsbakken et al. (2010):



define W ≡ no. of electrons whose state we need to change.

For flux qubit (because of indistinguishability of electrons),

$$W_{FQ} \sim N(\mathrm{v}/\mathrm{v}_F) \lesssim 5{,}000$$

"not macro- or even mesoscopic"

$N$: total number of electrons in penetration depth

$\mathrm{v}$: mean velocity of circulating electrons

However: if we compare stationary and moving states of smallest visible dust particle,

$$W_{DP} \sim 1{,}500\ !$$

So: are we already at the level of "everyday life"?

So: where do we go from here?

(What are the interesting "axes"?)

Simply larger physical scale: probably not so interesting

greater complexity/biological organization?

– e.g. human visual system

…..

connection with the "arrow of time"??

(1875 analogy)