Is Quantum Mechanics the Whole Truth?*

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1. Why bother?
2. What are we looking for?
3. What have we seen so far?
4. Where do we go from here?

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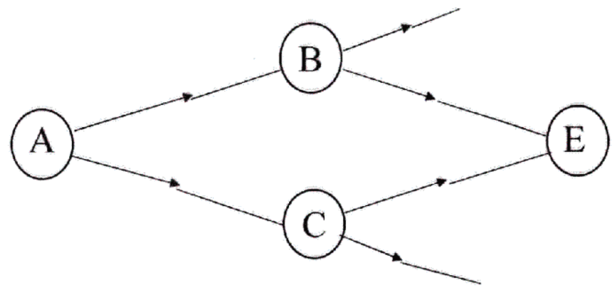
INTERFERENCE OF AMPLITUDES IN QM



MEASURE: $P_{A\to B\to E}$ (shut off channel C)

$P_{A\to C\to E}$ (shut off channel B)

$P^{tot}_{A\to E}$ (both channels open)

EXPTL. FACT:

$$P^{tot}_{A\to E} \neq P_{A\to B\to E} + P_{A\to C\to E}$$

QM ACCOUNT:

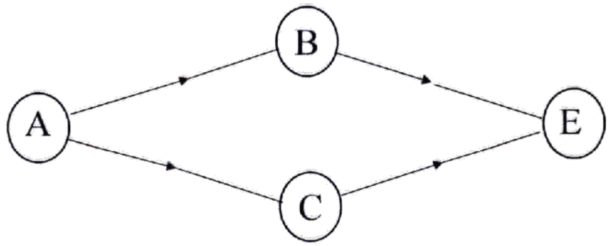
$$P^{tot}_{A\to E} = \left| \sum_{paths} A^{(path)}_{A\to E} \right|^2$$

vanishes unless **both** A's nonzero

$$= P_{A\to B\to E} + P_{A\to C\to E} + 2\mathrm{Re}(A_{A\to B\to E} \cdot A^*_{A\to C\to E})$$

⇒ amplitude must be finite for each of two paths, not just for ensemble but for each member of it

And yet….



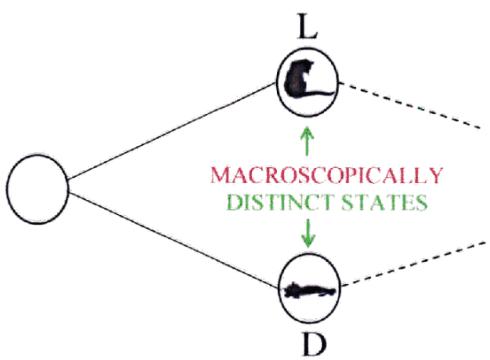
At microlevel:

Directly observed phenomenon of interference

⇒ simultaneous "existence" of amplitudes for two alternative paths for each individual member of ensemble

⇒ neither outcome "definitely realized"

Now, extrapolate formalism to macrolevel (Schrödinger):



Is each cat of ensemble either in state L or in state D?

POSSIBLE HYPOTHESES:

A. QM is the complete truth about the world, at both the microscopic (μ) and macroscopic (M) levels.

Then:

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

DOES THE VANISHING OF THE EVIDENCE PERMIT RE-INTERPRETATION OF THE MEANING OF THE QM FORMALISM?

B. QM is not the complete truth about the world: at M level other (non-QM) principles enter.

⇒ superpositions of macroscopically distinct states do not (neccessarily) exist (Ex: GRWP)

("MACROREALISM")

Q: Is it possible to discriminate experimentally between hypotheses (A) and (B) (at a given level of "macroscopicness")?

A: Yes, if and only if we can observe Quantum Interferance of Macroscopically Distinct States (QIMDS).

What is appropriate measure of "macroscopicness" ("Schrödinger's cattiness") of a quantum superposition?

↑: Definition should not make nonexistence of QIMDS a tautology!

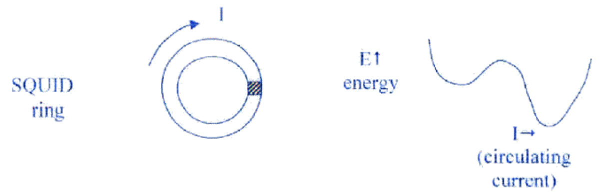
(My) proposed measures:

(1) Difference in expectation value of one or more extensive physical quantities in 2 branches, in "atomic" units. ("A")

(2) Degree of "disconnectivity" (≅ entanglement): how many "elementary" objects behave (appreciably) differently in 2 branches? ("D")

↑: quantum-optical systems, tunnelling Cooper pairs…are NOT strongly entangled with their environments!

(1) + (2) $\Rightarrow$ concept of macroscopic variable.



PROGRAM:

Stage 1: Circumstantial tests of applicability of QM to macrovariables.

Stage 2: Observation (or not!) of QIMDS given QM'l interpretation of raw data.

Stage 3: EITHER (a) exclude hypothesis B (macro-realism) independently of interpretation of raw data,

OR (b) exclude hypothesis A (universal validity of QM).

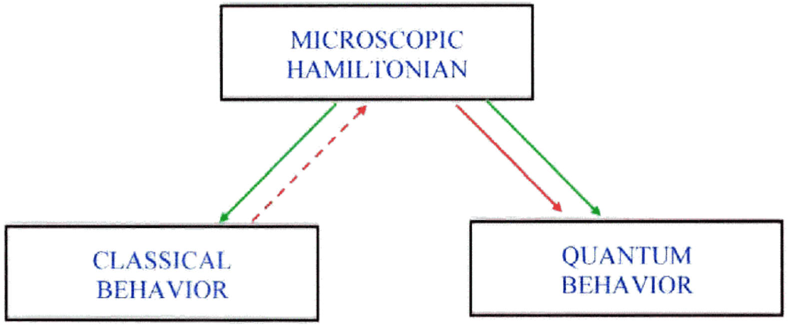
Objections:

(1) Macrovariable $\Rightarrow S >> \hbar \Rightarrow$ predictions of QM indistinguishable from those of CM.

Solution: Find macrovariable whose motion is controlled by microenergy.

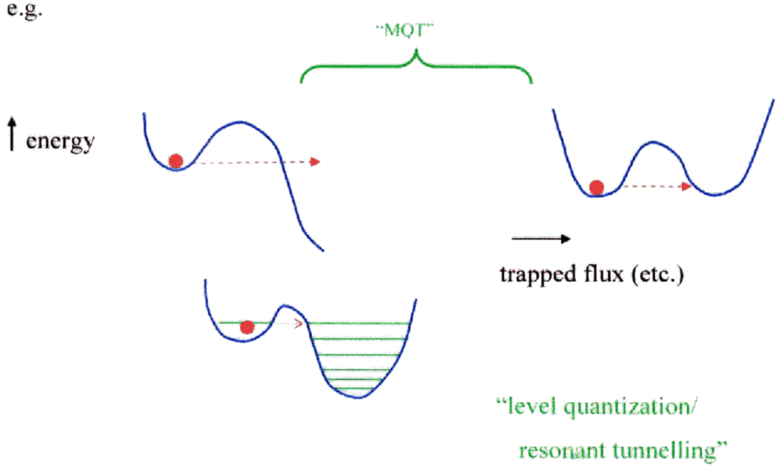
(2) Decoherence $\Rightarrow$ stage 2 impossible in practice.
Solution: Find system with very small dissipation.

(3) Hamiltonian of macrosystem unknown in detail $\Rightarrow$ can never make QM'l predictions with sufficient confidence to draw conclusion (3b).



Stage 1. Circumstantial tests of applicability of QM to macroscopic variables.
(mostly Josephson junctions and SQUIDS)

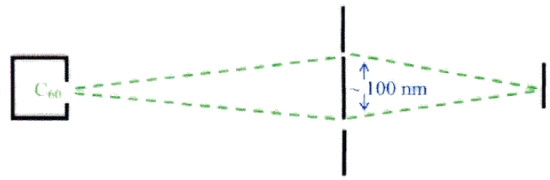
e.g.



Tests conjunction of (a) applicability of QM to macrovariables
(b) treatment of dissipation
Not direct evidence of QIMDS.

The Search for QIMDS

A. Molecular Diffraction (Vienna, 2000)



Note: (a) beam does not have to be monochromated
(b) $T_{oven} \sim 900$ K $\Rightarrow$ many vibrational modes excited

B. Magnetic Biomolecules (IBM, 1989)

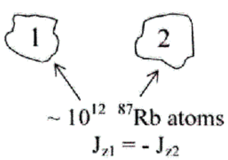
Evidence for QIMDS: resonance absorption of rf field, noise
If correct, $D \sim N$ (total no. of spins per molecule)
Note: ensemble of systems, only total magnetization measured

C. Quantum-Optical Systems (Aarhus, 2001)

$\langle \delta J_{x1}\, \delta J_{y1} \rangle \geq |J_{z1}|$ ($\neq 0$)

$\langle \delta J_{x2}\, \delta J_{y2} \rangle \geq |J_{z2}|$ ($\neq 0$)

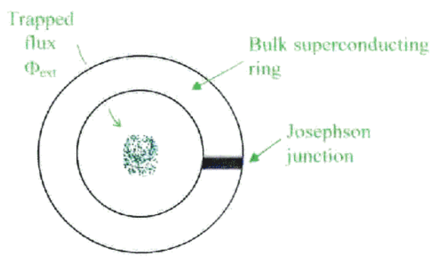
but, $\langle \delta J_{xtot}\, \delta J_{ytot} \rangle > \geq |J_{ztot}| = 0$!



"macroscopic" EPR-type correlations
Note: $D \sim N^{1/2}$ not $\sim N$.
(probably generic for this type of expt.)

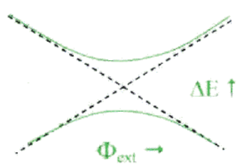
The Search for QIMDS (cont.)

D. Josephson circuits



$\Psi = 2^{-1/2}$ (|↺> + |↻>)

Evidence: (a) spectroscopic:
(SUNY, Delft 2000)



(b) real-time oscillations (like NH_3)

between ↺ and ↻

(Saclay 2002, Delft 2003) (Q_φ ~ 50-100)

SYSTEM	"EXTENSIVE DIFFERENCE"	DISCONNECTIVITY/ ENTANGLEMENT
Single e^-	1	1
Neutron in interferometer	~ 10^9	1
QED cavity	~ 10	≲ 10
Cooper-pair box	~ 10^5	2
C_{60}	~ 1100	~ 1100
Ferritin	~ 5000 (?)	~ 5000
Aarhus quantum-optics expt.	~ 10^6 ($\propto N^{1/2}$)	~ 10^6
SUNY SQUID expt.	~ 10^9 - 10^{10} ($\propto$ N)	~10^9 - 10^{10}
Smallest visible dust particle	~ 10^{22}	~ 10^{16}
Cat	~ 10^{34}	~ 10^{25}

Where do we go from here?

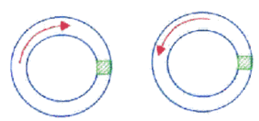
1. Larger values of Λ and/or D?
   (Diffraction of virus?)

2. Alternative Dfs. of "Measures" of Interest

   — More sophisticated forms of entanglement?
   — Biological functionality (e.g. superpose states of rhodopsin?)
   — Other (e.g. GR)

* 3. Exclude Macrorealism

Suppose: Whenever observed, Q = ± 1.



Q = + 1 Q = - 1

Df. of "MACROREALISTIC" Theory:

"COMMON SENSE"?

I. Q(t) = ± 1 at (almost) ∀ t,
   whether or not observed.

II. Noninvasive measurability

III. Induction

Can test with existing SQUID Qubits!

Tests of macrorealism versus quantum mechanics using SQUID

For a SQUID, define the class of macrorealistic theories by the postulates

(i) System always in either state + or state - , whether or not observed.

(ii) Can in principle determine whether + or - without effect on subsequent behavior ("noninvasive measurability").

(iii) Induction

There is a certain quantity K, whose value can be directly inferred from an appropriate series of measurements. Predictions for K:

(a) Any macrorealistic theory: $K \leq 2$ √

(b) Quantum mechanics, ideal: $K = 2.8$ √

(c) Quantum mechanics, with all the real-life complications: $K > 2$ (but < 2.8) (?)

Thus: to extent analysis of (c) within quantum mechanics is reliable, can force nature to choose between macrorealism and quantum mechanics!

Possible outcomes of SQUID experiment.

a) Experiment doesn't work (i.e., too much "noise" $\Rightarrow$ quantum-mechanical prediction for K is < 2).

b) $K>2 \Rightarrow$ macrorealism refuted.

c) $K<2 \Rightarrow$ quantum mechanics refuted at everyday level.