Title: QIMDS:probing quantum mechanics towards the macroscopic world

Date: Jul 19, 2006 02:45 PM

URL: http://pirsa.org/06070046

Abstract: If one is worried by the quantum measurement problem,a natural question to ask is: Does the quantum-mechanical description of the world retain its validity when its application leads to superpositions of states which by some reasonable criterion are _macroscopically distinct_? Or rather, does any such superposition automatically get "collapsed", even in the absence of "measurement" by a human observer, into one or other of its branches? Scenarios which predict the latter (for example the GRWP theory) may be denoted generically by the term "macrorealistic".

Even if one believes that QM remains the whole truth at the macrolevel, it is clear that to the extent that environmental decoherence destroys the delicate phase relations characterizing the superposition, the predictions of QM will be indistinguishable experimentally from those of the class of macrorealistic theories (a remark which is often taken, in my opinion quite erroneously, as "solving" the measurement problem). Thus, to distinguish experimentally between QM and macrorealism one needs a system in which decoherence is low enough that (given that QM is correct) one has a realistic chance of observing _quantum interference of macroscopically distinct states_ ("QIMDS"). Over the last few years, a surprising variety of candidate systems has emerged; however, while all experiments to date have been consistent with the continued validity of QM, none has so far refuted macrorealism outright. In this talk I review the systems in question and discuss the prospects for a truly definitive experiment.

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Quantum Interference of Macroscopically Distinct States

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Conference in honor of Abner Shimony

Perimeter Institute

July 2006

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

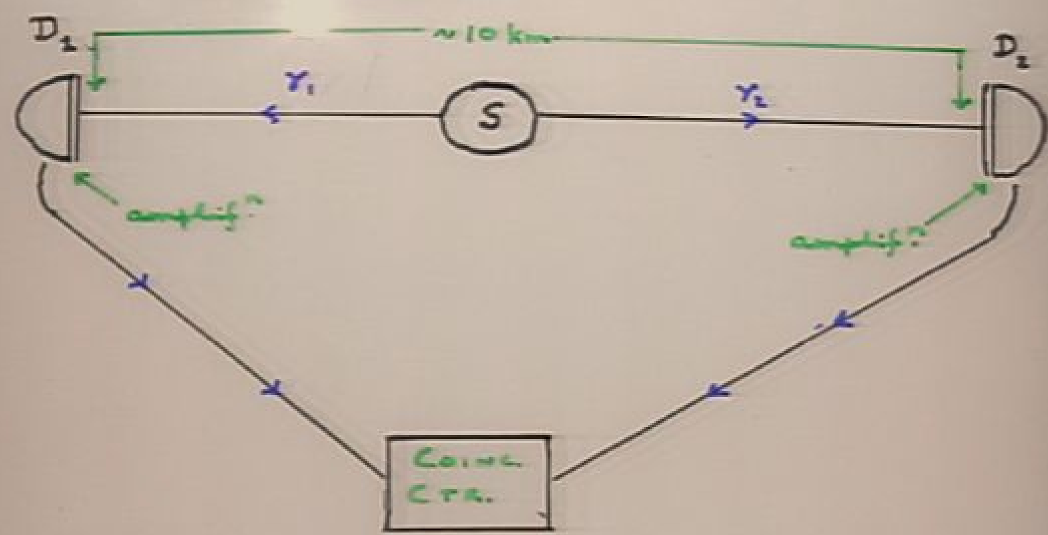
DOES THE VANISHING OF THE EVIDENCE PERMIT RE-INTERPRETATION OF THE MEANING OF THE QM FORMALISM?

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

$\Rightarrow$ superpositions of macroscopically distinct states do not (neccessarily) exist (Ex: GRWP)

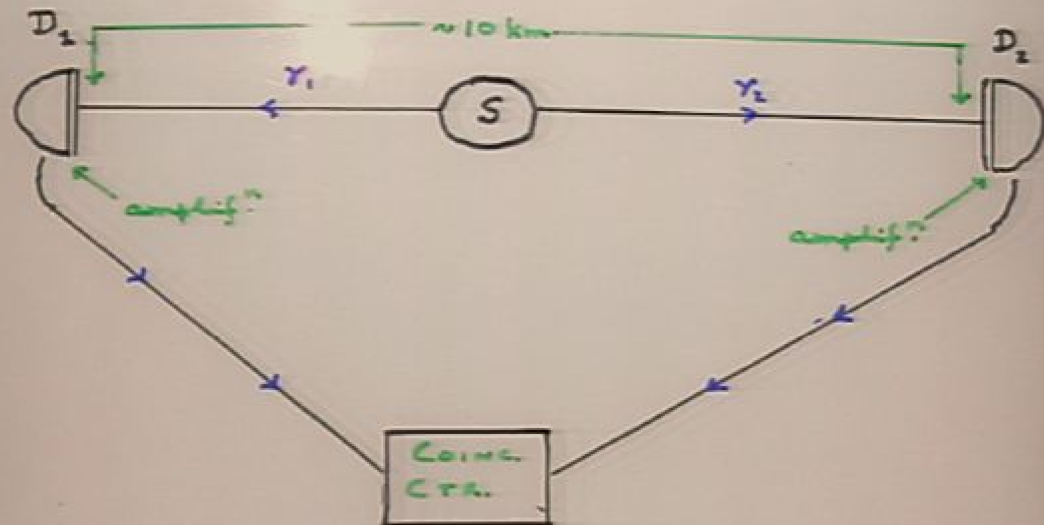
("MACROREALISM")

Do EPR-Bell Expts. already rule out Macrorealism?



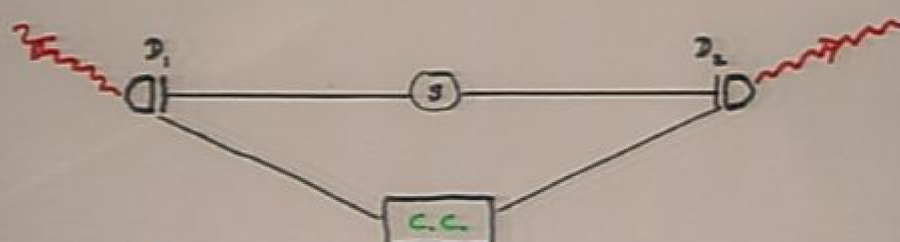
How late can we leave the "Realization"?

Do EPR-Bell Expts. already rule out Macro-realism?



How late can we leave the "Realization"?

A: "Third-Party" Effects!



In a (local) Macrorealistic Theory, 3rd-Party Correl^ns must be different from predictions of QM

A: Do we know QM pred^ns are right?

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⇒ 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 Interference 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. ("Δ")

(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) ⇒ concept of macroscopic variable.

EXAMPLES OF "PSEUDO-DISCONNECTIVITY"

(a) QED CAVITY

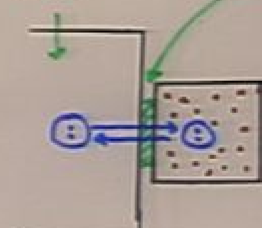
Naive description: $|\psi\rangle = \alpha|\gamma\rangle + \beta|vac\rangle$

Correct " : $|\Psi\rangle = \alpha|\gamma\rangle|\epsilon_1\rangle + \beta|vac\rangle|\epsilon_2\rangle$

states of e^- in walls

$|\langle\epsilon_1|\epsilon_2\rangle|^2 = \; ?$

(b) COOPER-PAIR BOX



Naive: $|\psi\rangle = \alpha|N\rangle_{res}|0\rangle_{box} + \beta|N-2\rangle_{res}|2\rangle_{box}$

Correct:

$$|\Psi\rangle = \alpha|N\rangle_{res}|0\rangle_{box}|\epsilon_1\rangle + \beta|N-2\rangle_{res}|2\rangle_{box}|\epsilon_2\rangle$$

states of other 10^9 e^-'s in box

$|\langle\epsilon_1|\epsilon_2\rangle|^2 = \; ?$

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).

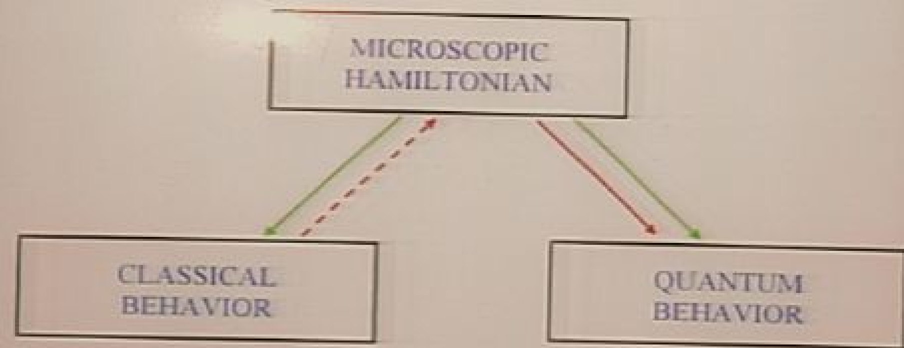
Objections:

(1) Macrovariable $\Rightarrow S \gg \hbar \Rightarrow$ 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.

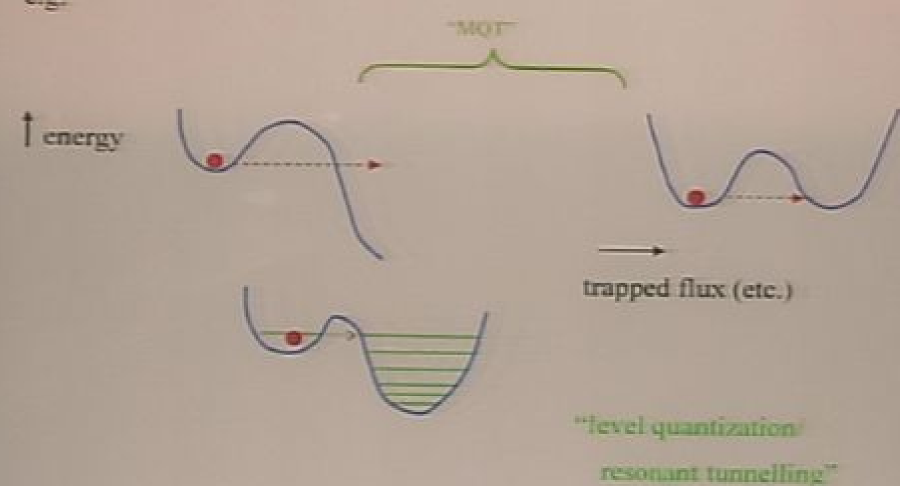
(3) Hamiltonian of macrosystem unknown in detail $\Rightarrow$ can never make QM'l predictions with sufficient confidence to draw conclusion (3b).



Stage 1. Circumstantial tests of applicability of QM to macroscopic variables.

(mostly Josephson junctions and SQUIDS)

e.g.



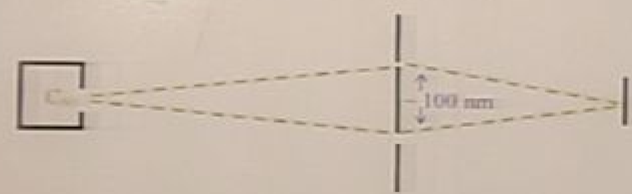
Tests conjunction of (a) applicability of QM to macrovariables

(b) treatment of dissipation

Not direct evidence of QIMDS.

The Searc… …s

A. Mole… …ffraction (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)

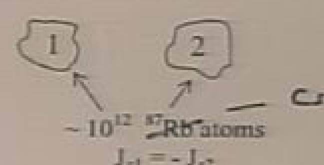
Evidence for QIMDS: resonance absorption of rf field, noise
If correct, D ~ N (total no. of spins per molecule)
Note: ensemble of systems, only total magnetization measured

C. Quantum-Optical Systems (Aarhus, 2001)

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

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

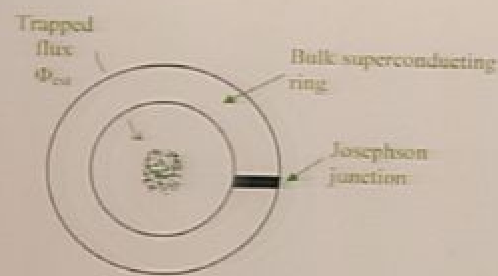
but, $\langle \delta J_{xtot}\, \delta J_{ytot} \rangle >> \geq |J_{ztot}| = 0$!

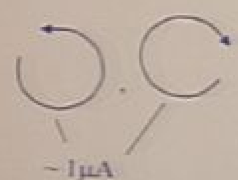


"macroscopic" EPR-type correlations
Note: D ~ $N^{1/2}$ not ~N.
(probably generic for this type of expt.)

The Search for QI [illegible] ont.)

D. Josephson circuits





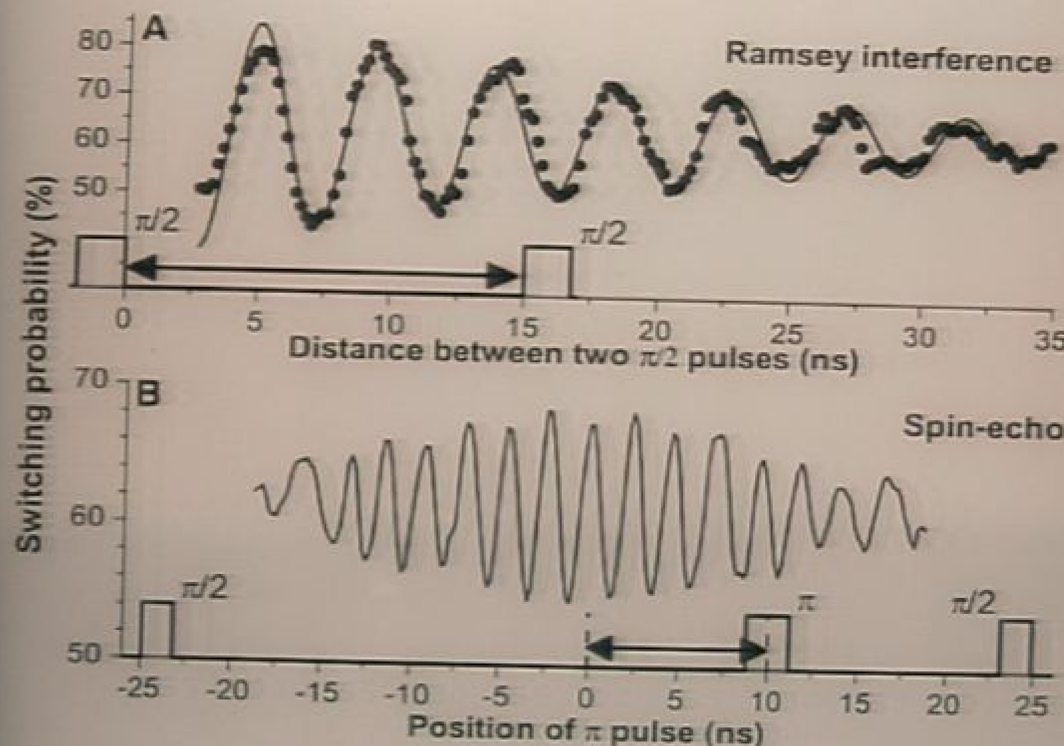
$$\Psi = 2^{-1/2}\,(|\circlearrowleft\rangle + |\circlearrowright\rangle)$$

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

(b) real-time oscillations (like NH_3)

between ↺ and ↻

(Saclay 2002, Delft 2003) (Q_e ~ 50-350)

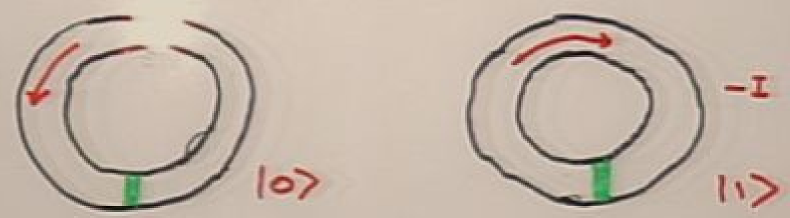


From I. Chiorescu, Y. Nakamura, C.J.P. Harmans, and J. E. Mooij, Science, 299, 1869 (2003)

SYSTEM	"EXTENSIVE DIFFERENCE"	DISCONNECTIVITY/ ENTANGLEMENT
Single e^-	1	1
Neutron in interferometer	$\sim 10^9$	1
QED cavity	~ 10	≤ 10
Cooper-pair box	$\sim 10^5$	2
C_{60}	~ 1100	~ 1100
Ferritin	~ 5000 (?)	~ 5000
Aarhus quantum-optics expt.	$\sim 10^6$ ($\propto N^{1/2}$)	$\sim 10^6$
SUNY SQUID expt.	$\sim 10^9 - 10^{10}$ ($\propto N$)	
Smallest visible dust particle	$\sim 10^{22}$	$\sim 10^{16}$
Cat	$\sim 10^{34}$	$\sim 10^{23}$

ITLEM 10a

"DISCONNECTIVITY" IN FLUX QUBIT



How many microscopic objects are "behaving differently" in 2 states?

A. Normal metal:

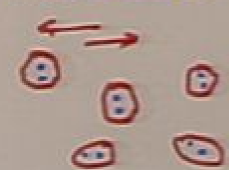
$D \sim I/ev_F$

($\sim 10^4 - 10^5$ in SUNY expt)

B. Tightly bound diatomic molecules:

$D = N/2$

($\sim 10^9 - 10^{10}$)



C. Cooper pairs

$D \sim N_0 \sim (\Delta/\epsilon_F)N$ ← no. of pairs (max: eigenvalue of $\hat{\rho}_2$)

($\sim 10^6 - 10^7$ for SUNY expt.)

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, $Q = \pm 1$.

$Q = +1$ $Q = -1$

Df. of "MACROREALISTIC" Theory:

"COMMON SENSE"?

I. $Q(t) = \pm 1$ at (almost) $\forall$ t,

whether or not observed.

II. Noninvasive measurability

III. Induction

Can test with existing SQUID Qubits!

Deriv^n of CHSH Inequality for Time Correlations

Dichotomic variable $Q(t)$ (e.g. flux in rf SQUID), whenever measured, $Q(t) = \pm 1$

Postulates of macrorealistic theory:

(1) $Q(t) = \pm 1 \quad \forall t$ [exc. for small "transit time"]

(2) Noninvasive measurability

(3) Induction

Consider experimentally measurable quantity

$$K_{exp} \equiv \langle Q(t_1)Q(t_2)\rangle_{exp} + \langle Q(t_2)Q(t_3)\rangle_{exp} + \langle Q(t_3)Q(t_4)\rangle_{exp} - \langle Q(t_1)Q(t_4)\rangle_{exp}$$

Then:

(1) $\Rightarrow$ on any given run,

$$K \equiv Q(t_1)Q(t_2) + Q(t_2)Q(t_3) + Q(t_3)Q(t_4) - Q(t_1)Q(t_4) \leq 2$$

(2) $\Rightarrow \langle K\rangle_{ens} \leq 2$

(2+3) $\Rightarrow \langle K\rangle_{exp} = \langle K\rangle_{ens}$

$\Rightarrow K_{exp} \leq 2$ in any MR theory

QM: $(t_2 - t_1 = t_3 - t_{[illegible]}$ [illegible] $- t_3 = \pi/4\Delta)$ ("ideal")

$K = 2$[illegible]

CAS 19 (10)

Possible outcomes of SQUID experiment.

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

b) $K>2$ ⇒ macrorealism refuted.

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