Is Quantum Mechanics the Whole Truth?*

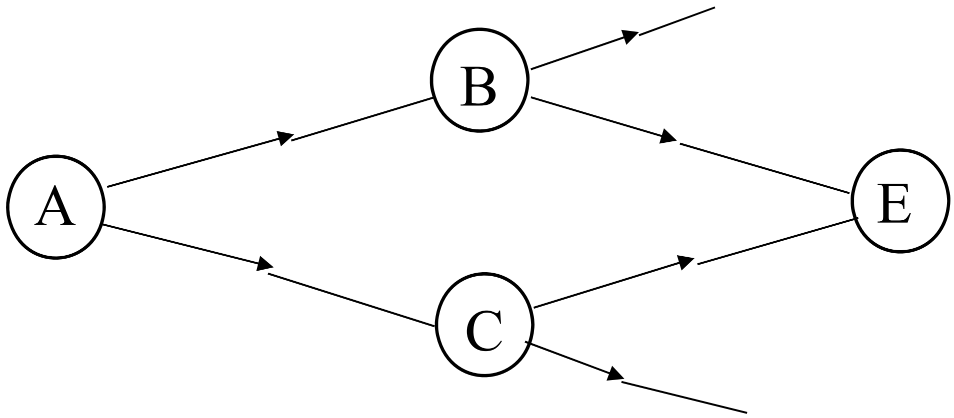
A.J. Leggett

University of Illinois at Urbana-Champaign

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

*J. Phys. Cond. Mat. **14**, R415 (2002)
Reps. Prog. Phys. **71**, 022001 (2008)

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

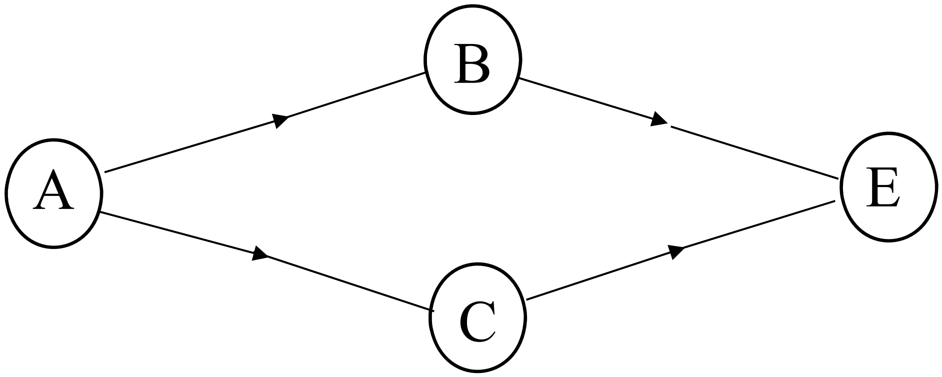
QM ACCOUNT: $$P^{tot}_{A\to E} = \left| \sum_{paths} A^{(path)}_{A\to E} \right|^2$$

vanishes unless both A's nonzero

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

$\Rightarrow$ amplitude must be nonzero for each of two paths, not just for ensemble but for each member of it

And yet….



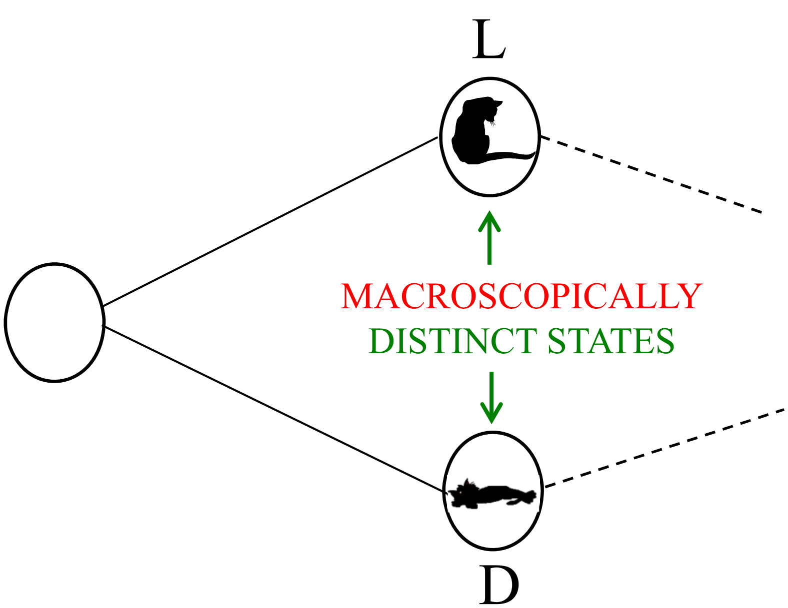
At microlevel:

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

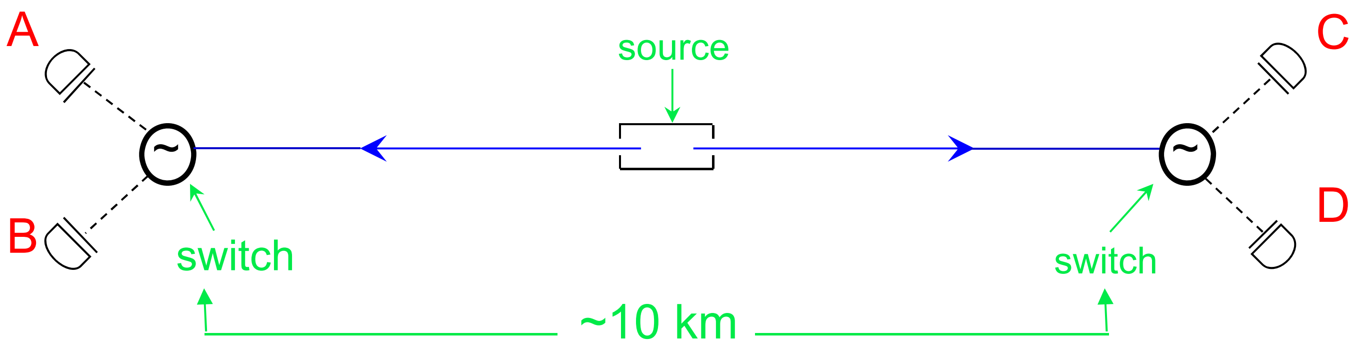
DOES THE VANISHING OF THE EVIDENCE PERMIT RE-INTERPRETATION OF THE MEANING OF THE QM FORMALISM?

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 (necessarily) exist (Ex: GRWP)

("MACROREALISM")

Do "EPR-Bell" Expts. Already Exclude Macrorealism?



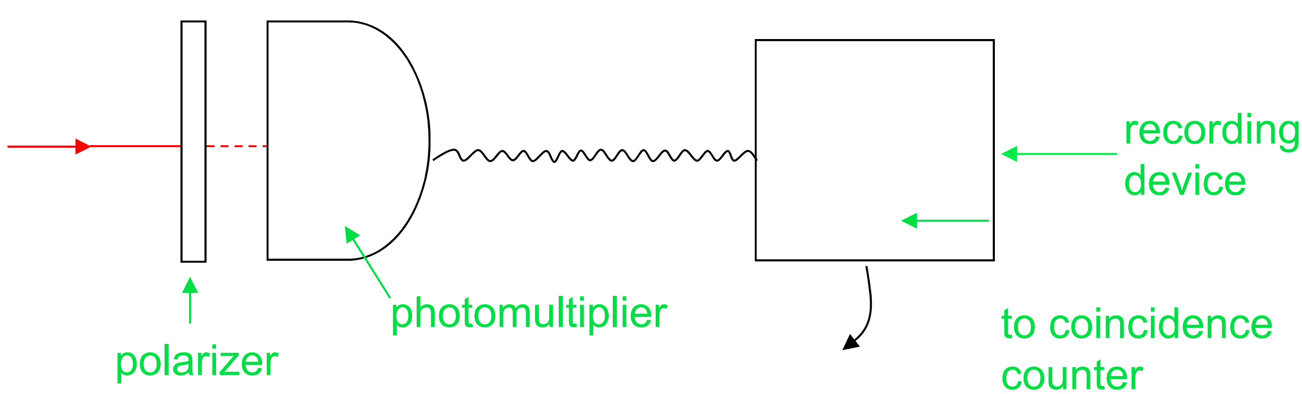
Experimental results (consistent with predictions of QM and) inconsistent with any theory embodying conjunction of

1. Induction
2. Locality
3. Microscopic realism or macroscopic counterfactual definiteness (MCFD)

MCFD ≠ macrorealism!

nevertheless: ∃ no "local" instruction set . . .

When does "realization" take place?



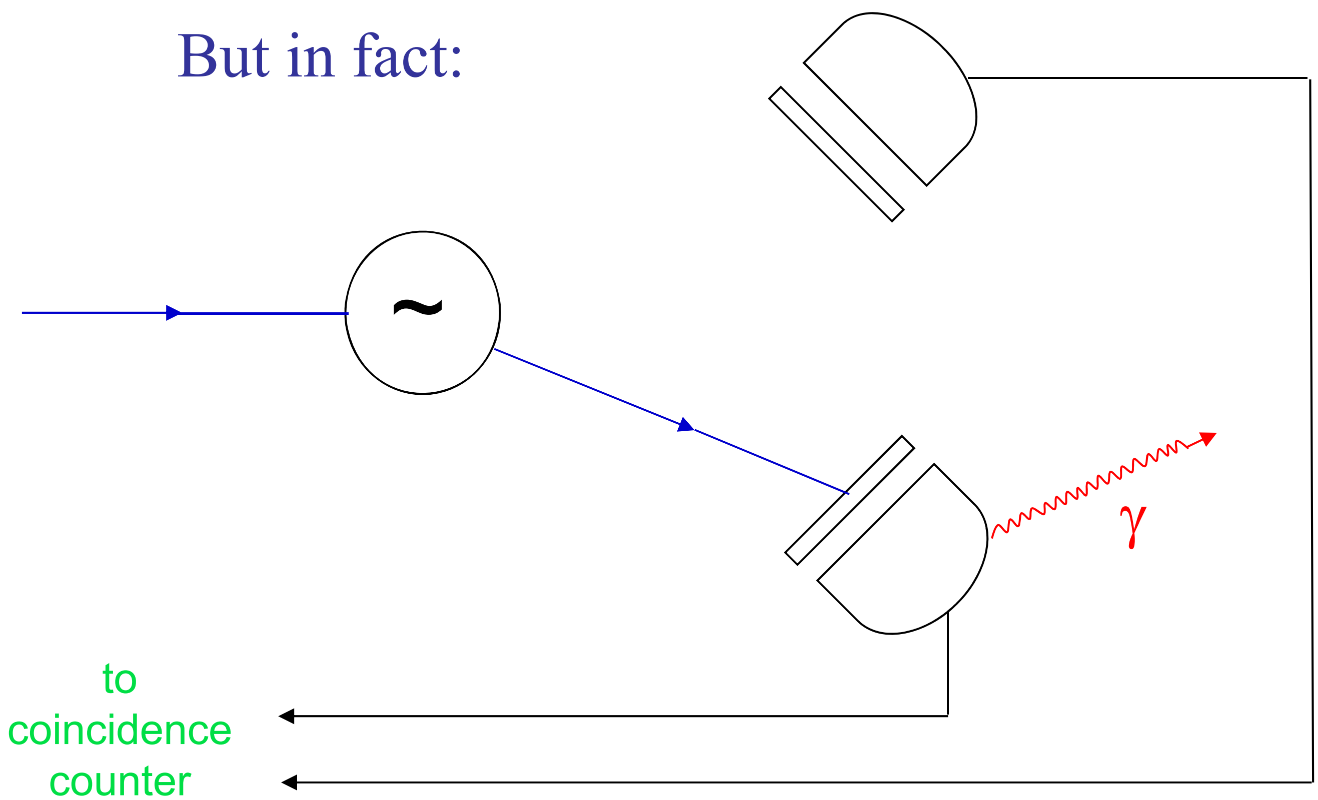
EPR-Bell Expts: The "Third-Party" Problem

Prima facie, for eg 0^+ transition, QM description after both detectors have had chance to fire is

$$\Psi_{QM} = 2^{-1/2}\left\{\cos\Theta_{ab}\left(|Y_1\rangle|Y_2\rangle + |N_1\rangle|N_2\rangle\right) + \sin\Theta_{ab}(|Y_1\rangle|N_2\rangle + |N_1\rangle|Y_2\rangle)\right\}$$

($|Y\rangle$ = "fired", $|N\rangle$ = "not fired")

But in fact:



$$\Psi_{QM} \sim 2^{-1/2}\{\cos\Theta_{ab}|Y_1\rangle|Y\rangle|E_1\rangle|E_2\rangle + \ldots\}$$?!

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:

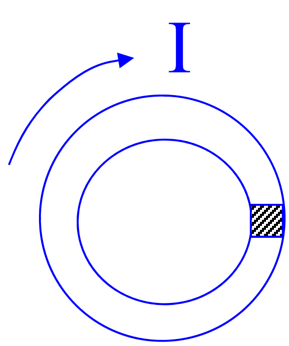
(1) Difference in expectation value of one or more extensive physical quantities in 2 branches, in "atomic" units. ("Λ")

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

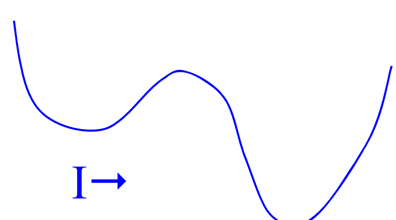
↑:quantum-optical systems, tunnelling Cooper pairs…are NOT strongly entangled with their environments!

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

SQUID ring



E↑ energy



I→ (circulating current)

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).

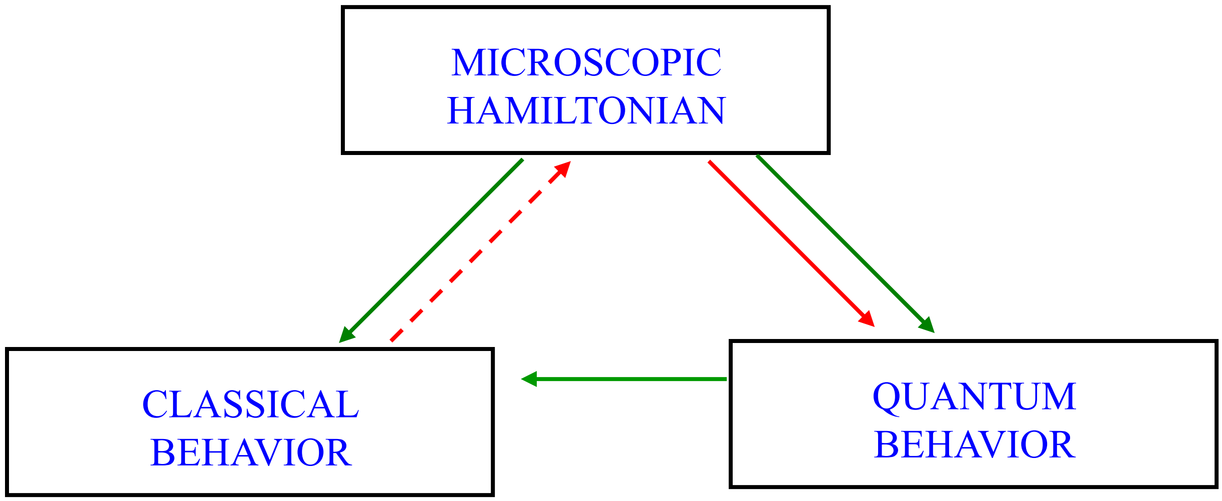
Objections:

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

Solution: Find macrovariable whose motion is controlled by microenergy.

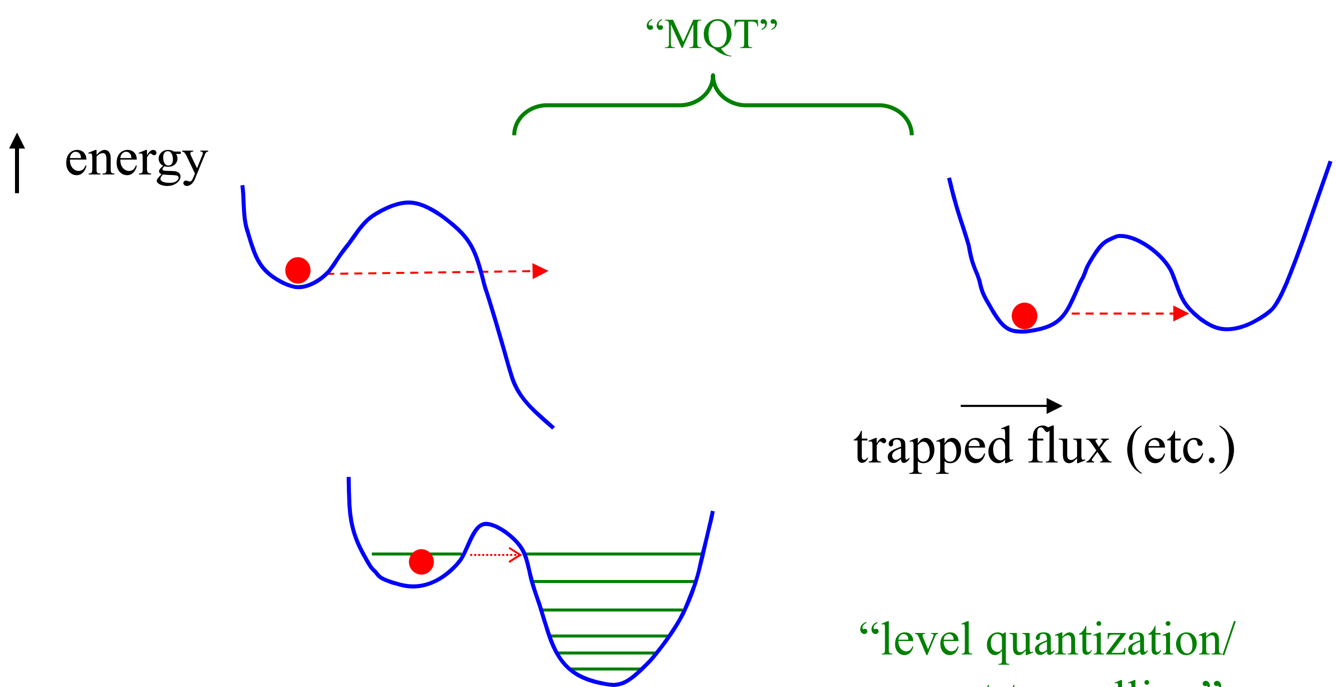
(2) Decoherence $\Rightarrow$ stage 2 impossible in practice. Solution: Find system with very small dissipation.

(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.

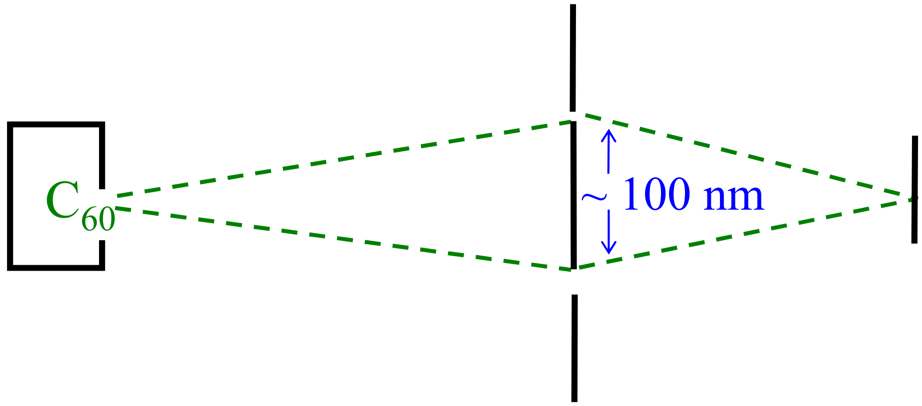


Tests conjunction of (a) applicability of QM to macrovariables
(b) treatment of dissipation

Not direct evidence of QIMDS.

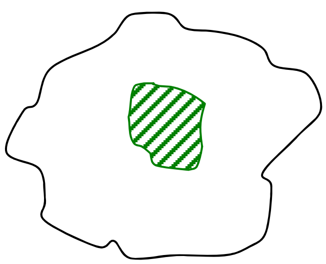
The Search for QIMDS

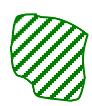
A. Molecular Diffraction (Vienna, 2000)



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

B. Magnetic Biomolecules (1BM, 1989)





$\cong 5000$ Fe^{3+} ions (in matrix)

$|\uparrow\uparrow\uparrow\uparrow\ldots\rangle$ or $|\downarrow\downarrow\downarrow\downarrow\ldots\rangle$

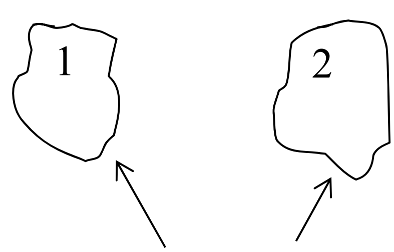
Evidence for QIMDS: resonance absorption of rf field, noise
If correct, D ~ N (total no. of spins per molecule)
Note: ensemble of systems, only total magnetization measured

C. Quantum-Optical Systems (Aarhus, 2001)

$<\delta J_{x1}\, \delta J_{y1}>$ □ $|J_{z1}|$ $(\neq 0)$

$<\delta J_{x2}\, \delta J_{y2}>$ □ $|J_{z2}|$ $(\neq 0)$

but, $<\delta J_{xtot}\, \delta J_{ytot}>$ □ $|J_{ztot}| = 0$!



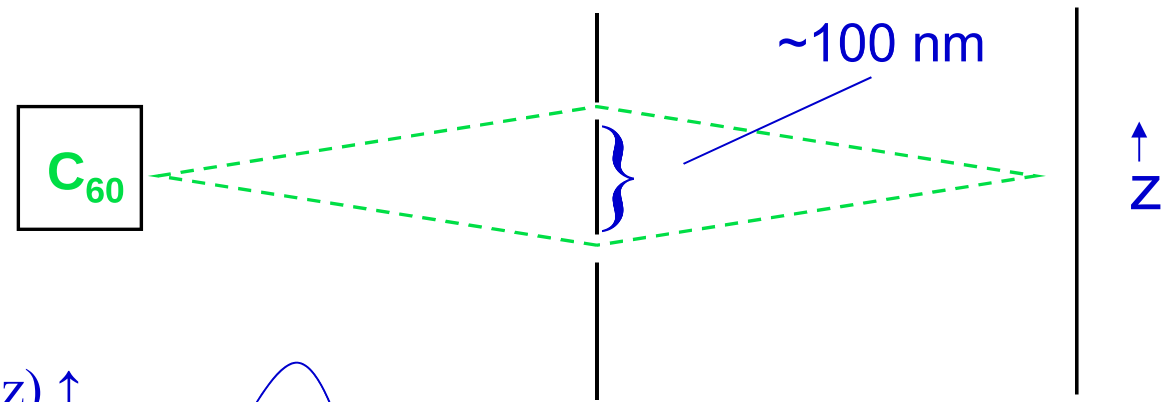
~ 10^{12} ^{87}Cs atoms

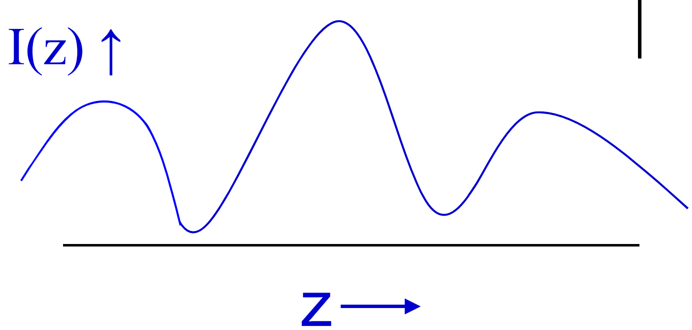
$J_{z1} = - J_{z2}$

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

The Search for QIMDS

1. Molecular diffraction*





Note: (a.) Beam does not have to be monochromated

$$f(\upsilon) = A\upsilon^3 \exp-(\upsilon-\upsilon_o)^2/\upsilon_m^2 \qquad (\upsilon_o \sim 1.8\,\upsilon_m)$$

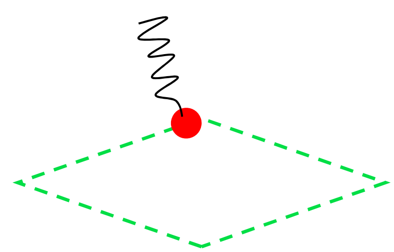
(b.) "Which-way" effects?

Oven is at 900–1000 K

⇒ many vibrational modes excited

4 modes infrared active ⇒

absorb/emit several radiation quanta on passage through apparatus!



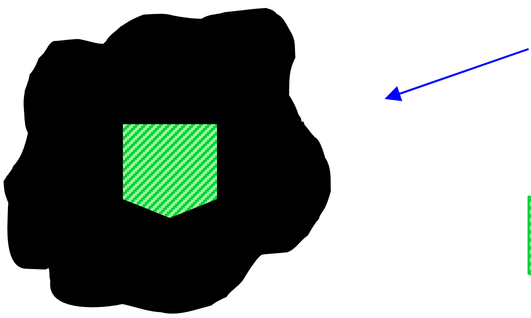
Why doesn't this destroy interference?

---

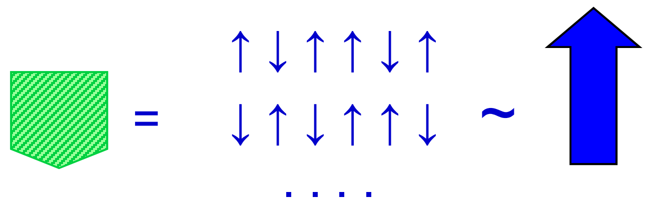
*Arndt et al., Nature *401*, 680 (1999)

The Search for QIMDS (cont.)

2. Magnetic biomolecules*



Apoferritin sheath
(magnetically inert)



(~5000 Fe^{3+} spins, mostly AF but slight ferrimagnetic tendency)
($M \sim 200\mu_B$)

$\alpha|\Uparrow\rangle + \beta|\Downarrow\rangle$?

$$\text{AF}: \Delta \sim \hbar\omega_o \exp - N\sqrt{K/J}$$

J: (isotropic) exchange en.
N: no. of spins
K: uniaxial anisotropy

Raw data: $\chi(\omega)$ and noise spectrum
above ~200 mK, featureless
below ~300 mK, sharp peak at ~ 1 MHz (ω_{res})

$$\omega_{res}^2 \cong \omega_o^2 + M^2 H^2$$

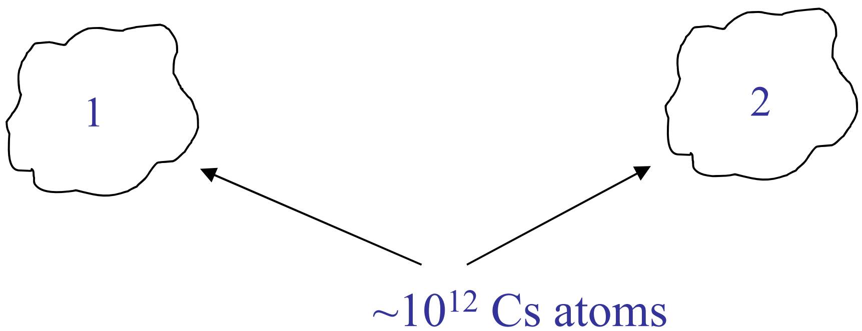
$$\ell n\ \omega_o \sim a - bN \leftarrow \text{no. of spins, exptly. adjustable}$$

Nb: data is on physical ensemble, i.e., only total magnetization measured.

*S. Gider et al., Science *268*, 77 (1995) (a.e.w.e.t.)

The Search for QIMDS (cont.)

3. Quantum-optical systems*



for each sample separately, and also for total

$$\left[J_x, J_y\right] = iJ_z$$

$$\Rightarrow \quad \left\langle \delta J_{x1} \delta J_{y1} \right\rangle \geq | J_{z1} |$$

$$\left\langle \delta J_{x2} \delta J_{y2} \right\rangle \geq | J_{z2} |$$

$$\left\langle \delta J_{xtot} \delta J_{ytot} \right\rangle \geq | J_{ztot} |$$

so, if set up a situation s.t. $J_{z1} = -J_{z2}$

must have $\left\langle \delta J_{x1} \delta_{y1} \right\rangle > 0$

$$\left\langle \delta J_{x2} \delta_{y2} \right\rangle > 0$$

but may have $\left\langle \delta J_{xtot} \delta J_{y\,tot} \right\rangle = 0$

(anal. of EPR)

---

*B. Julsgaard et al., Nature *41*, 400 (2001)

Interpretation of idealized expt. of this type:

(QM theory $\Rightarrow$) $\langle \delta J_{x1} \delta J_{y1} \rangle \geq | J_{z1} | \sim N$

$$\Rightarrow |\delta J_{x1}| \gtrsim N^{1/2}$$

But,

$$(\text{expt} \Rightarrow) \ \langle \delta J_{xtot} \delta J_{ytot} \rangle \cong 0$$

$$\Rightarrow |\delta J_{xtot}| \sim 0$$

$\Rightarrow \delta J_{x1}$ exactly anticorrelated with δJ_{x2}

$\Rightarrow$state is either superposition or mixture of |n,–n>

but mixture will not give (#)

value of J_{x1} value of J_{x2}

$\Rightarrow$ State must be of form

$$\sum_n c_n | n_1 - n >$$

with appreciable weight for $n \leq N^{1/2}$. $\Rightarrow$ high disconnectivity

Note:

(a) QM used essentially in argument
($\Rightarrow$ stage 2 not stage 3)

(b) D ~ $N^{1/2}$ not ~N.
(prob. generic to this kind of expt.)

The Search for QIMDS (cont.)

4. Superconducting devices

(↑: not all devices which are of interest for quantum computing are of interest for QIMDS)

Advantages:

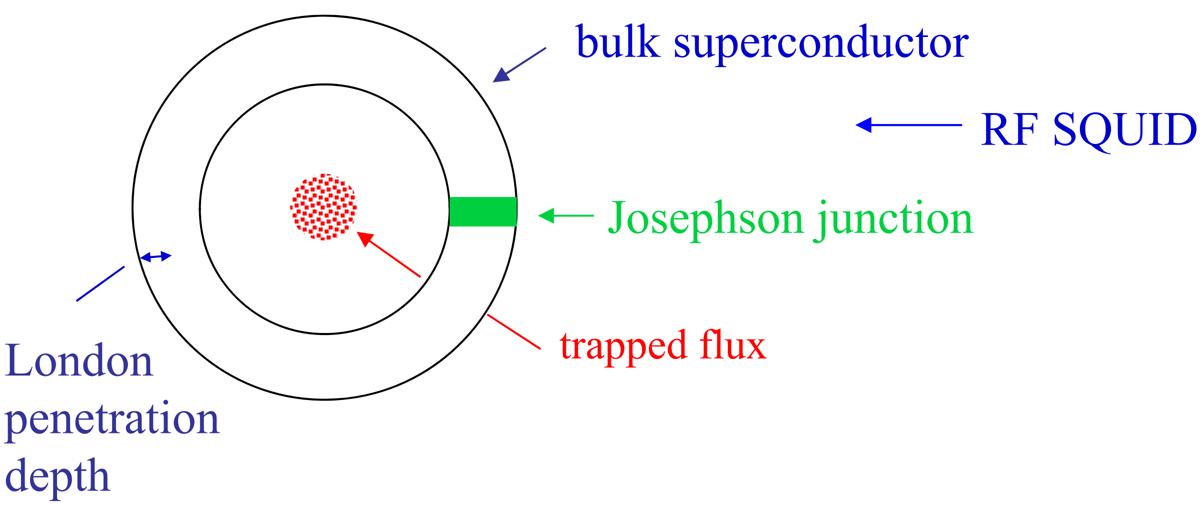
— classical dynamics of macrovariable v. well understood

— intrinsic dissipation (can be made) v. low

— well developed technology

— (non-) scaling of S (action) with D.

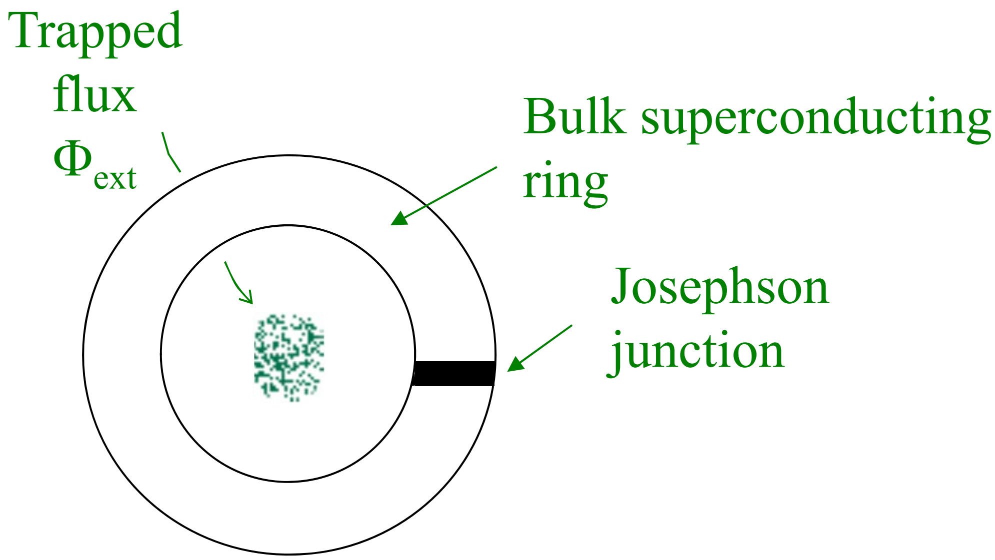
— possibility of stage-III expts.

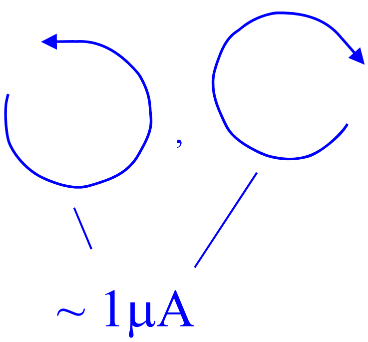


“Macroscopic variable” is trapped flux Φ
[or circulating current I]

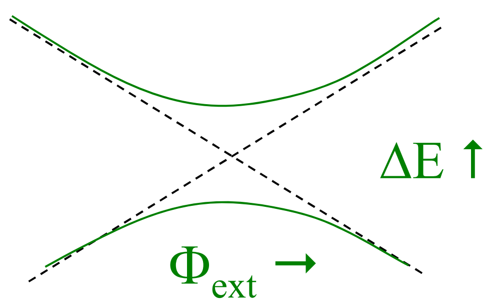
The Search for QIMDS (cont.)

D. Josephson circuits





$\Psi = 2^{-1/2}$ (|↺> + |↻>)

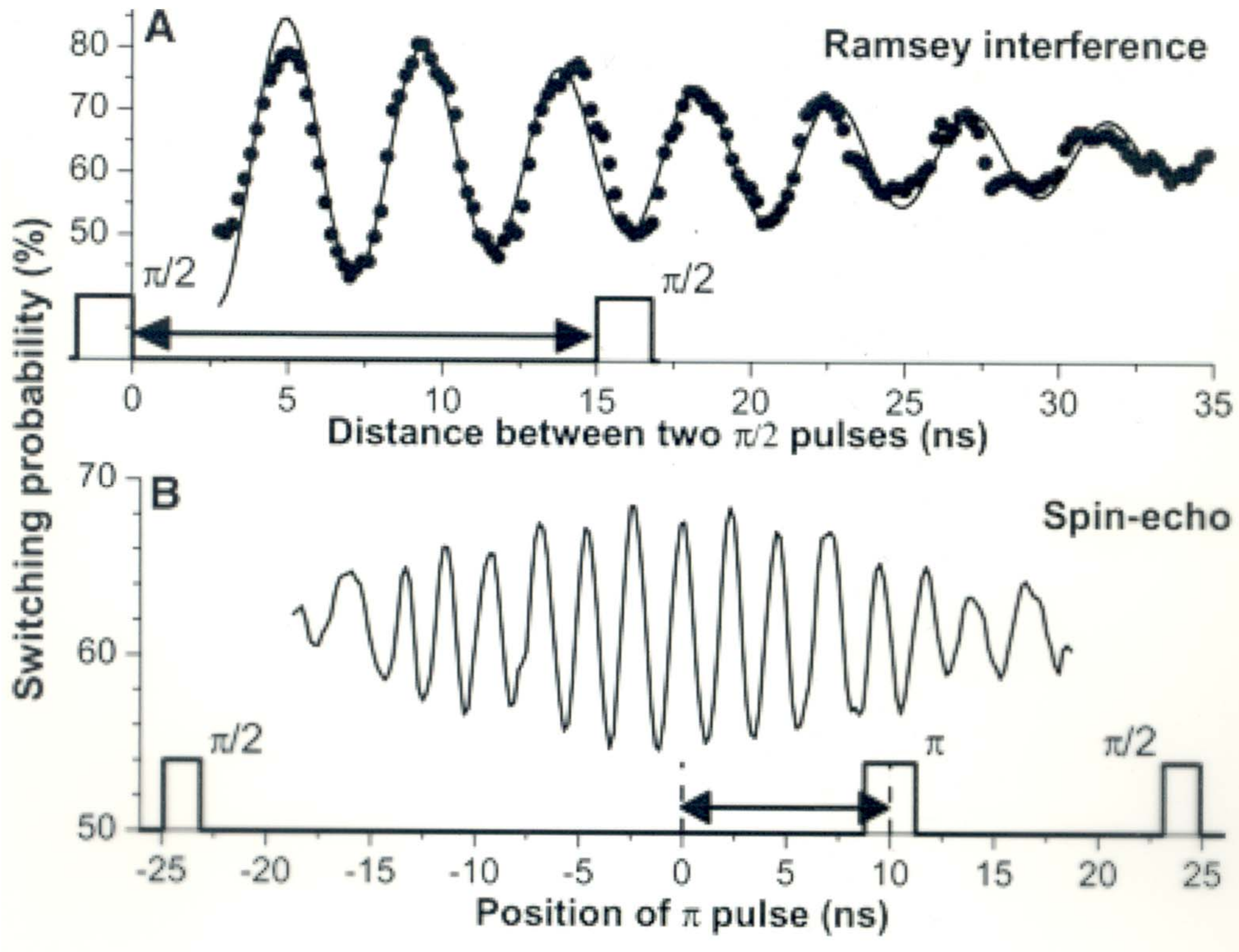


Evidence: (a) spectroscopic:
(SUNY, Delft 2000)

(b) real-time oscillations (like NH_3)

between ↺ and ↻

(Saclay 2002, Delft 2003) ($Q_\varphi \sim$ 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	$\lesssim 10$
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} ($\propto N$)	($10^4 – 10^{10}$)
Smallest visible dust particle	$\sim 10^{14}$	($10^3 – 10^{14}$)
Cat	$\sim 10^{34}$	$\sim 10^{25}$

Where do we go from here?

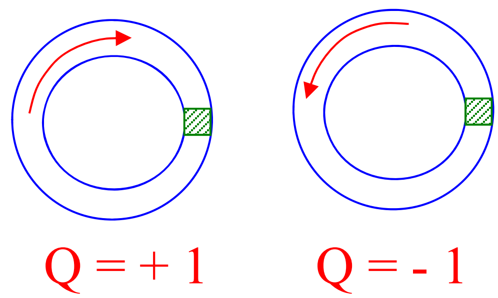
1. Larger values of Λ and/or D?
   (Diffraction of virus?)

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, $Q = \pm 1$.



Df. of "MACROREALISTIC" Theory:

"COMMON SENSE"?

I. $Q(t) = \pm 1$ at (almost) all t, whether or not observed.

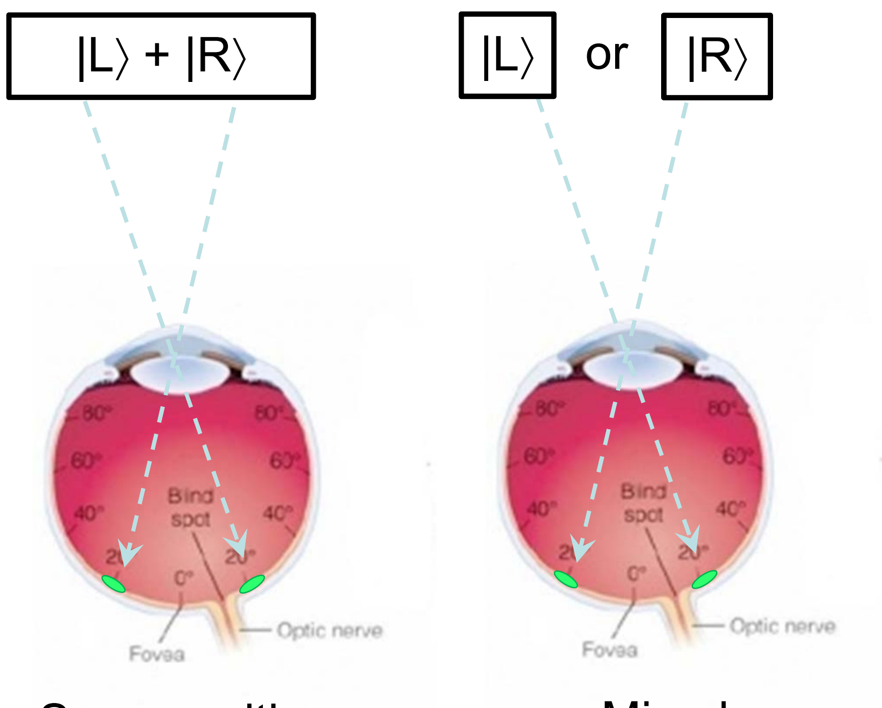
II. Noninvasive measurability

III. Induction

Can test with existing SQUID Qubits!

Phase 2: Superposition

- Methods
  - Two conditions
    - Superposition condition: N photons at $|L\rangle + |R\rangle$ state
    - Mixed condition: N photons each at $|L\rangle$ or $|R\rangle$ with equal probability
  - Observer judges whether a light was present on Left and on Right separately



Superposition condition

Mixed condition

- Data analysis
  - If the detection rates at L and/or R in the superposition condition is statistically different from that of the mixed condition, then QM is violated

Df:

$$K \equiv K(t_1 t_2 t_3 t_4) \equiv \left\langle Q(t_1) Q(t_2) \right\rangle_{\text{exp}} + \left\langle Q(t_2) Q(t_3) \right\rangle_{\text{exp}} + \left\langle Q(t_3) Q(t_4) \right\rangle_{\text{exp}} - \left\langle Q(t_1) Q(t_4) \right\rangle_{\text{exp}}$$

Take $t_2 - t_1 = t_3 - t_2 = t_4 - t_3 = \pi / 4\Delta$ ← tunnelling frequency

Then,

(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:

(1) Too much noise $\Rightarrow K_{QM} < 2$

(2) $K > 2 \Rightarrow$ macrorealism refuted

(3) $K < 2$: ? !