Title: The quantum realization paradox: theoretical considerations and experimental input (Part 1B)

Date: Aug 31, 2007 10:30 AM

URL: http://pirsa.org/07080055

Abstract:

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:

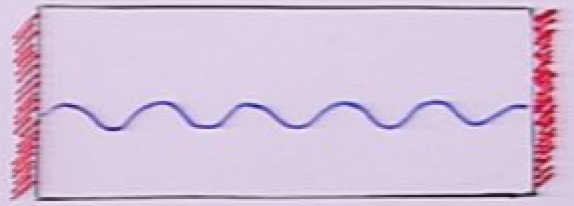
(1) Difference in expectation value of one or more extensive physical quantities in 2 branches, in "atomic" units. ("Δ")

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

[illegible] systems, tunnelling Cooper pairs ... are [illegible] strongly entangled with their environments!

(1) – (2), [illegible] concept of [illegible]

Ex. 1: QED Cavity (no atoms!)



Textbook description:

$$\psi = \alpha|0\rangle + \beta|\gamma\rangle$$

$\uparrow$ vac. $\quad$ $\uparrow$ 1 photon

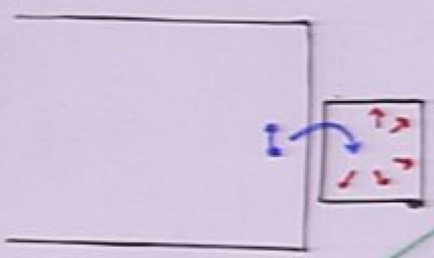
states of electrons in walls

? More sophisticated description:

$$\Psi_{univ} = \alpha|0\rangle|\chi_1\rangle + \beta|\gamma\rangle|\chi_2\rangle$$

$\langle\chi_1|\chi_2\rangle \approx 0$??

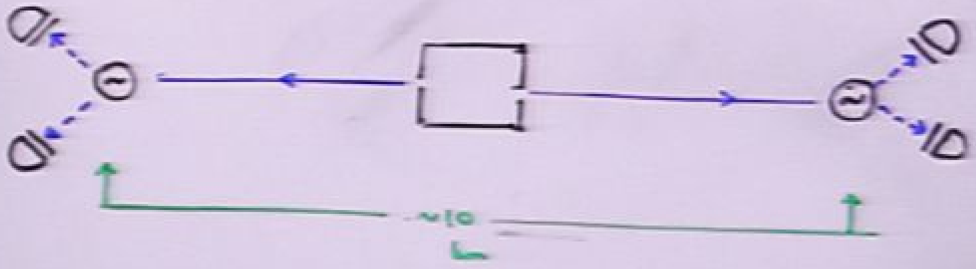
Ex. 2: Cooper-pair box



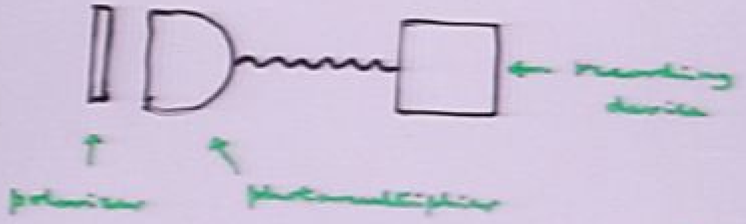
states of N electrons already in box

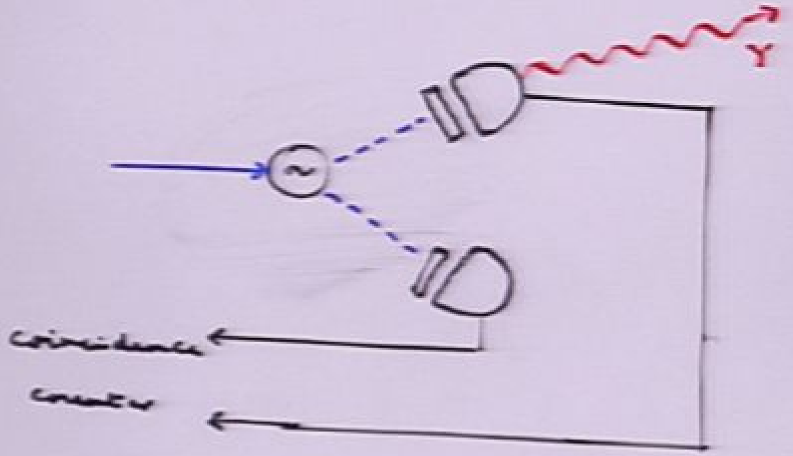
? $\Psi_{univ} \sim \alpha|out\rangle|\chi_1\rangle + \beta|in\rangle|\chi_2\rangle$

$\langle\chi_1|\chi_2\rangle \approx 0$??



When does "realization" take place?





If realization too much delayed, can never "recover" γ!

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).

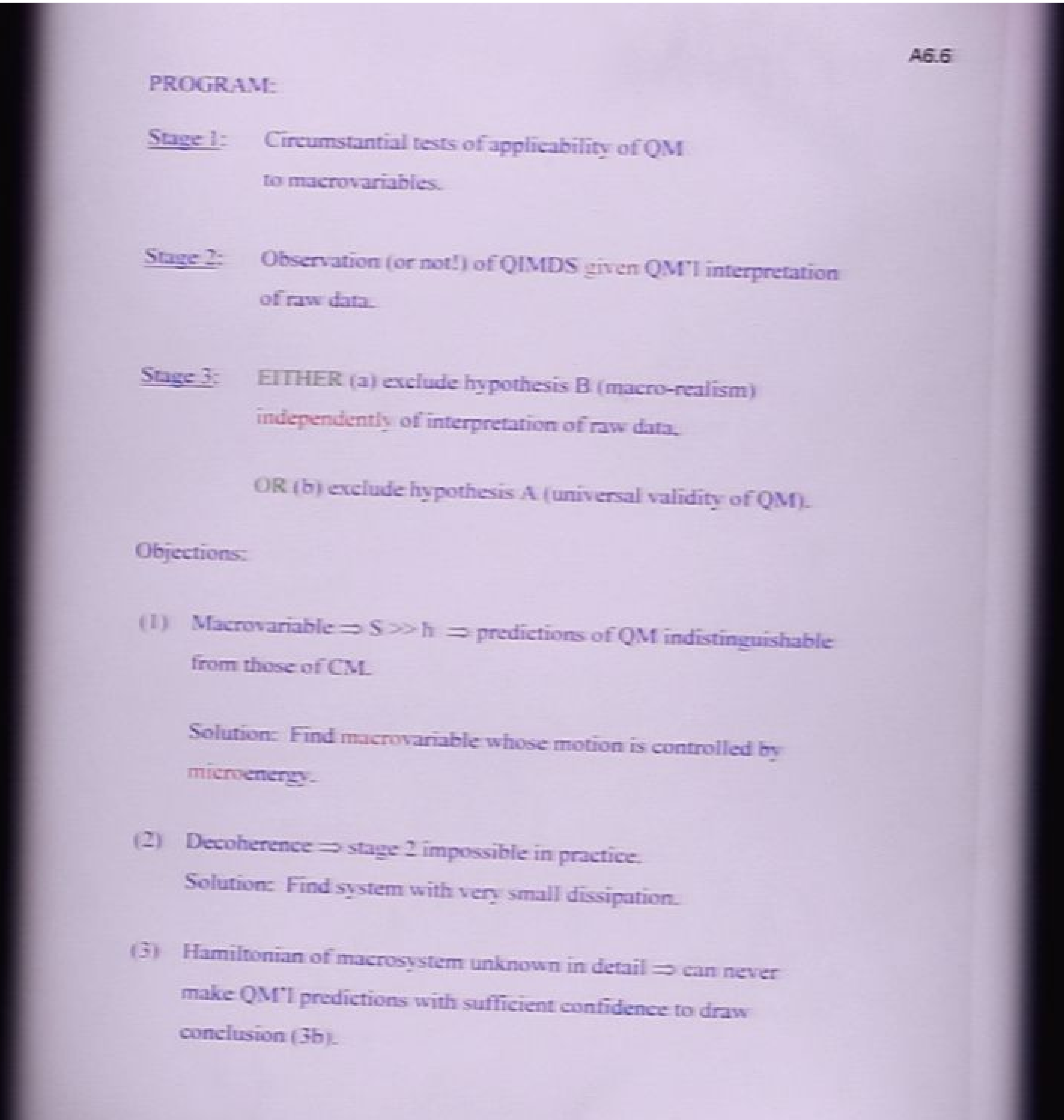
Objections:

(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).



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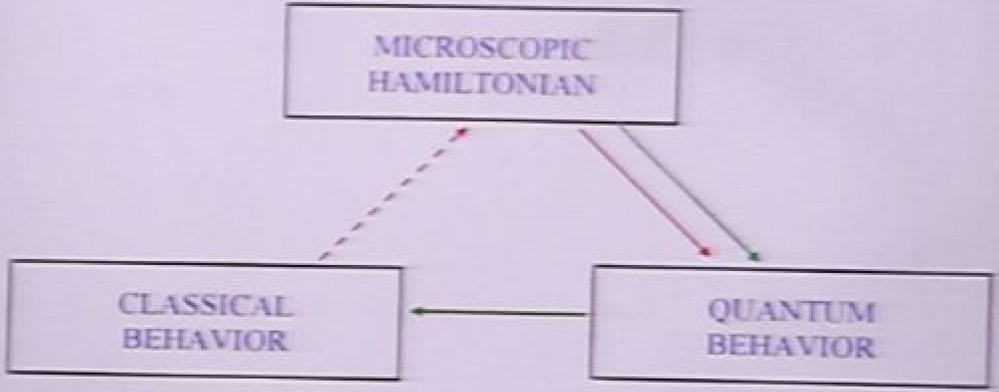


MICROSCOPIC HAMILTONIAN

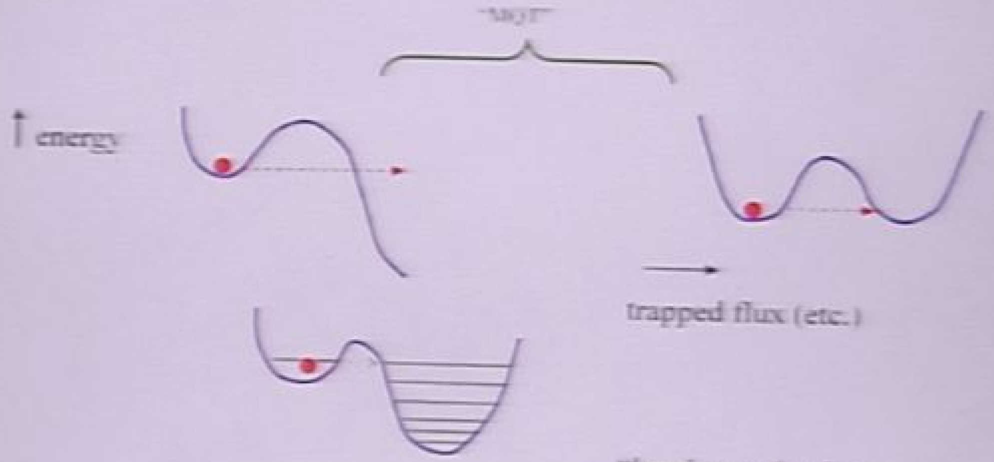
CLASSICAL BEHAVIOR

QUANTUM BEHAVIOR

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

(mostly Josephson junctions and SQUIDS)

e.g.



trapped flux (etc.)

"level quantization/
Resonant tunnelling"

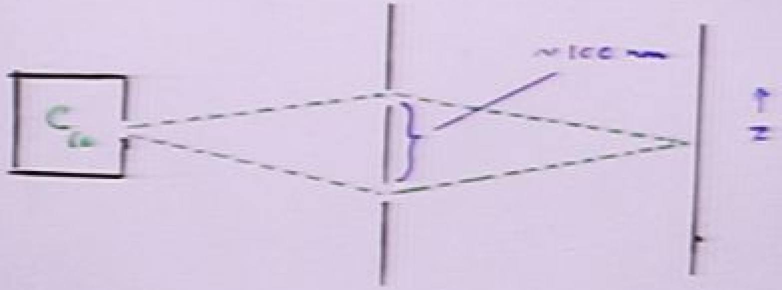
Tests conjunction of (a) applicability of QM to macrovariables

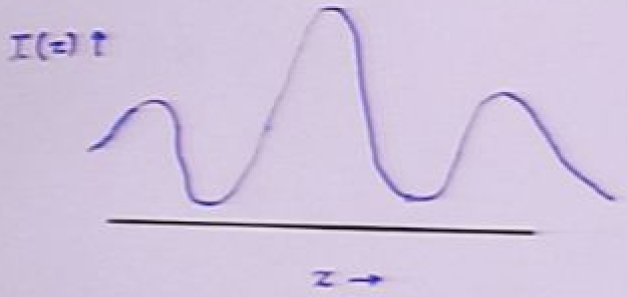
(b) treatment of dissipation

Not direct evidence of QIMDS.

THE SEARCH FOR QIMDS

1. Molecular diffraction*





1. Beam does not have to be monochromated

$$f(v) = Av^3 \exp-(v-v_0)^2/v_m^2 \qquad (v_0 \sim 1.5\, v_m)$$

2. "Which-way" effects?

even if at 900-1000 K

⇒ many vibr.l modes excited

+ modes infrared active ⇒

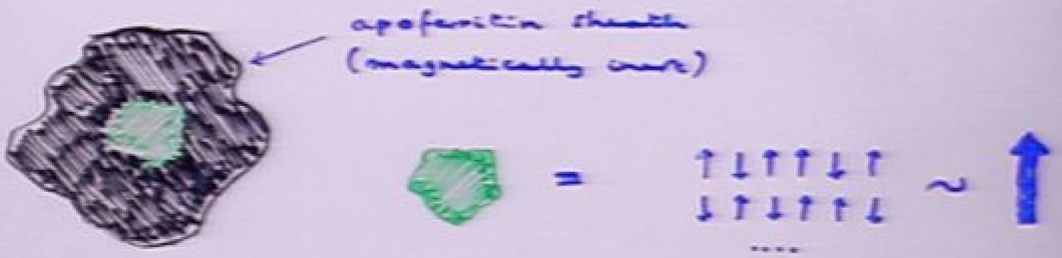
absorb/emit several rad.n quanta

on passage through apparatus!

Why doesn't

THE SEARCH FOR QIMDS (Cont.)

2. Magnetic biomolecules*



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

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

AF: $\Delta \sim \hbar\omega_0 \exp - \underset{\text{no. of spins}}{N}\sqrt{\underset{\text{uniaxial anisotropy}}{K}/J} \leftarrow$ (isotropic) exchange en.

Raw data: $\chi(\omega)$ and noise spectrum

above ~ 200 mK, featureless

below ~ 200 mK, sharp peak at ~ 1 MHz (ω_{res})

$$\omega_{res}^2 \cong \omega_0^2 + M^2H^2$$

$\ln \omega_0 \sim a - bN$ ← no. of spins, exptly. adjustable

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

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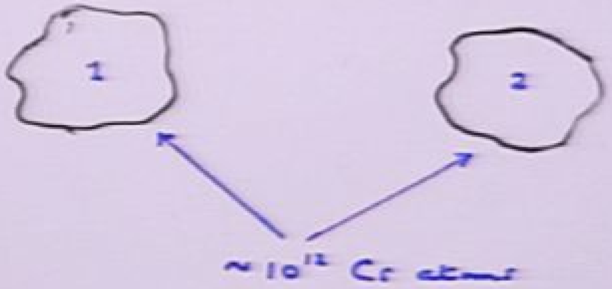
* S Gider et al. S

3. Quantum-optical systems*



for each sample separately, and also for total

$$[J_x, J_y] = iJ_z$$

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

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

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

so, if set up a situation s.t.

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

must have

$$\langle \delta J_{x1} \delta J_{y1} \rangle > 0$$

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

but

$$\langle \delta J_{xtot} \delta J_{ytot} \rangle = 0$$

(cond. of EPR)

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* B Julsgaard et al., Nature

Interpretation of idealized expt. of this type:

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

⇒ $|\delta J_{x1}| \gtrsim N^{1/2}$

<u>But</u>.

(expt ⇒) $\langle \delta J_{xtot} \delta J_{ytot} \rangle \cong 0$ (*)

⇒ $|\delta J_{xtot}| \sim 0$

⇒ δJ_{x1} exactly anticorrelated with δJ_{x2}.

⇒ state is either superpos^n or mixture of $|n, -n\rangle$

values of J_{x1}

values of J_{x2}

but mixture will not give (*)

⇒ state must be of form

$$\sum_n c_n |n, -n\rangle$$

with appreciable weight for $n \lesssim N^{1/2}$. ⇒ high disconn^y?

Note:

(a) QM used essentially in argt.

(⇒ stage 2 not stage 3)

(b) $D \sim N^{1/2}$ not $\sim N$.

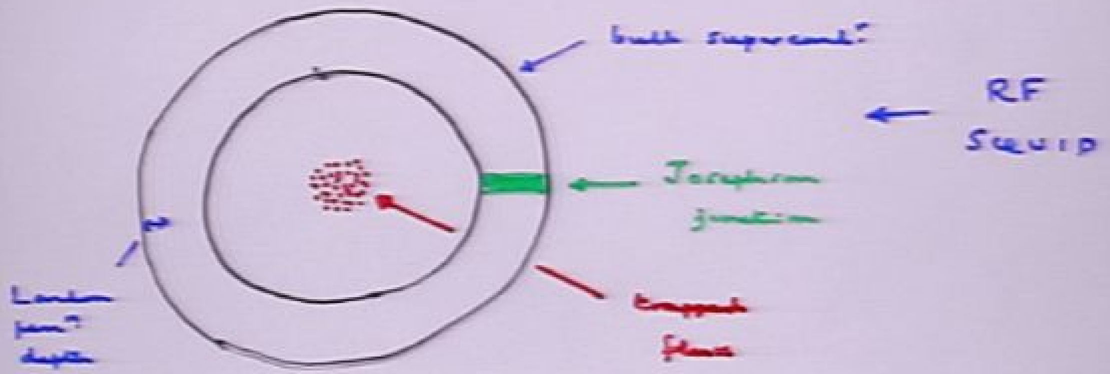
(prob. generic to this kind of expt.)

4. Superconducting devices

(4: 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]

QFS 7

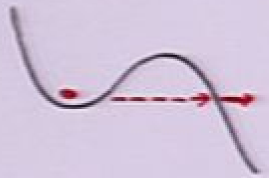
Quantum dynamics:

(a) conservative: $p_\Phi \rightarrow -i\hbar \frac{\partial}{\partial \Phi}$

$$i\hbar \frac{\partial \psi(\Phi:t)}{\partial t} = \hat{H}\psi \quad , \text{i.e.}$$

$$i\hbar \frac{\partial}{\partial t}\psi(\Phi:t) = \left\{ -\frac{\hbar^2}{2C}\frac{\partial^2}{\partial \Phi^2} + U(\Phi:t) \right\} \psi(\Phi:t)$$

so could calculate e.g.



"MQT"

"MQC"

However,

(b) the \$64K question:

how to describe effects of dissipation in QM terms?

oscillator-bath model:

$$\hat{H} = \hat{H}_0(q, p_q) + \text{SHO's} - q\sum_i C_i x_i \quad (+\text{c'term})$$

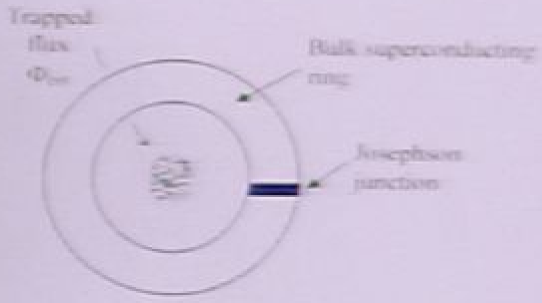
$$\sum_i |C_i|^2/(m_i\omega_i)\,\delta(\omega-\omega_i) \equiv J(\omega) = \eta\omega.$$

$\nearrow$ friction coeff^t in classical motion

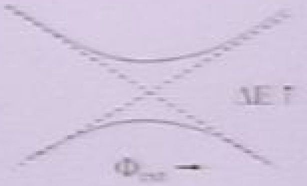
$\Rightarrow$

The Search for QIMDS (cont.)

D. Josephson circuits



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

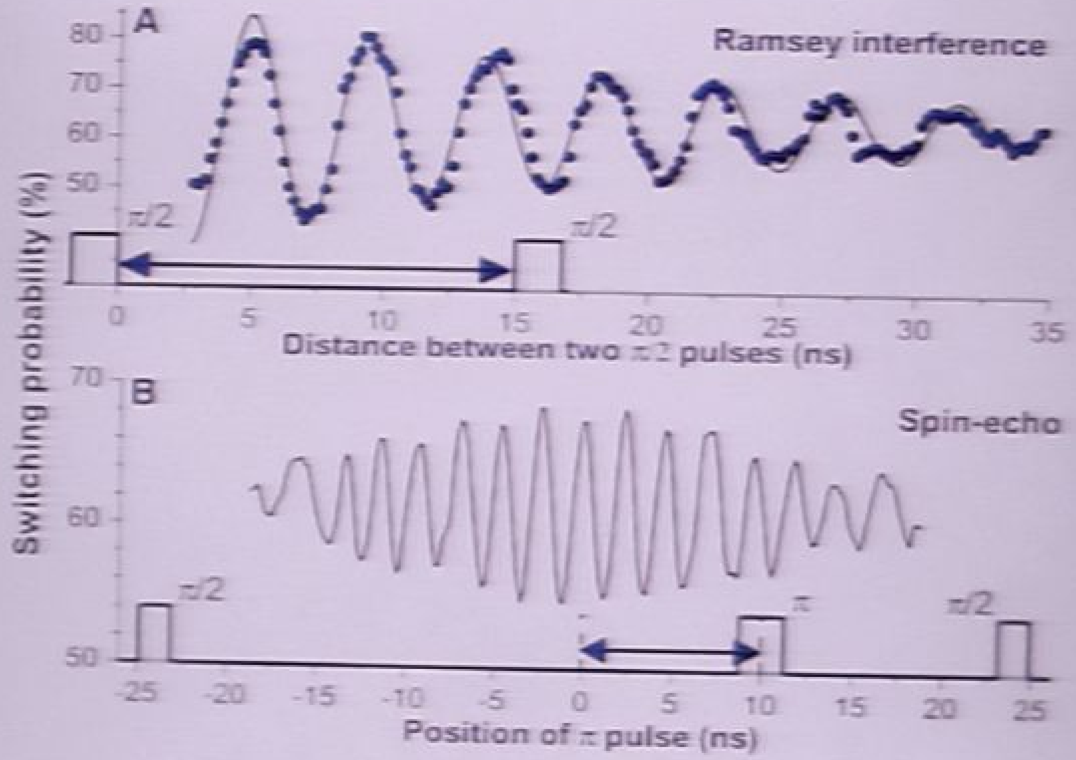


Evidence: (a) spectroscopic:
(SUNY, Delft 2000)

(b) real-time oscillations (like NH_3)

between ↺ and ↻

(Saclay 2002, Delft 2003) $(Q_\varphi \sim 50\text{-}350)$



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.	$\sim 10^9 - 10^{10}$ $(\propto N)$	$(10^3–10^{10})$
Smallest visible dust particle	$\sim 10^{22}$	$\sim 10^{18}$
Cat	$\sim 10^{34}$	$\sim 10^{28}$

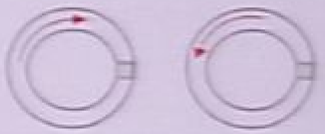
Where do we go from here?

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!

Df:

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

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)

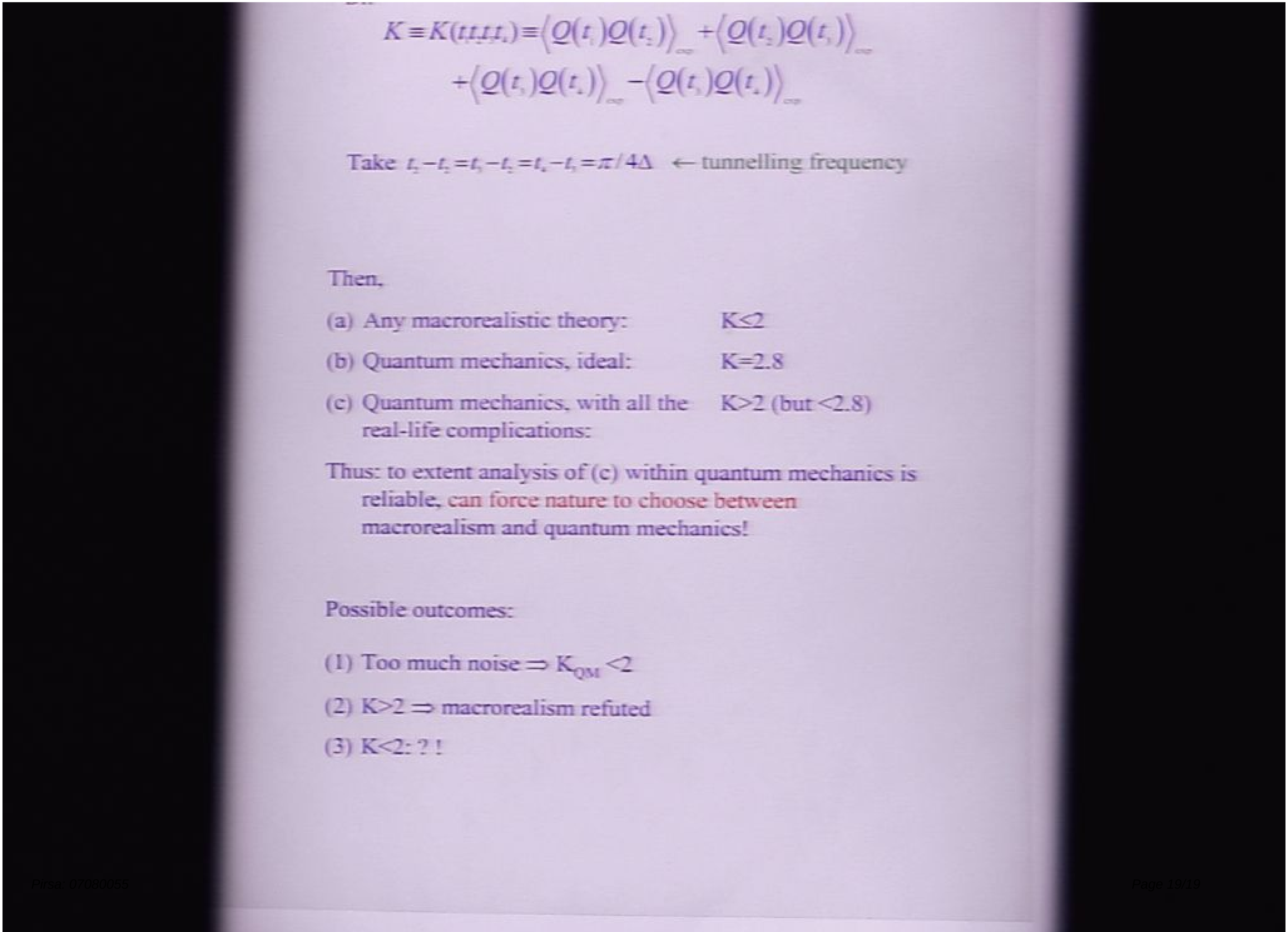
Thus: to extent analysis of (c) within quantum mechanics is reliable, can force nature to choose between macrorealism and quantum mechanics!

Possible outcomes:

(1) Too much noise ⇒ $K_{QM} < 2$

(2) $K > 2$ ⇒ macrorealism refuted

(3) $K < 2$: ? !



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