TESTING QUANTUM MECHANICS TOWARDS THE LEVEL OF EVERYDAY LIFE: RECENT PROGRESS AND CURRENT PROSPECTS

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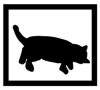
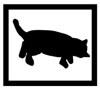
MESO/MACROSCOPIC TESTS OF QM: MOTIVATION

At microlevel: (a) $|\uparrow\rangle + |\downarrow\rangle$ quantum superposition ✓

$\neq$ (b) $|\uparrow\rangle$ OR $|\downarrow\rangle$ classical mixture ×

how do we know? Interference

At macrolevel: (a)  +  quantum superposition

OR (b)  OR  macrorealism

⚠: Decoherence DOES NOT reduce (a) to (b)!

Can we tell whether (a) or (b) is correct?

Yes, if and only if they give different experimental predictions. But if decoherence → no interference, then predictions of (a) and (b) identical.

⇒ must look for QIMDS

quantum interference of macroscopically distinct states

What is “macroscopically distinct”?

(a) “extensive difference” Λ

(b) “disconnectivity” D

~large number of particles behave differently in two branches

Initial aim of program: interpret raw data in terms of QM, test (a) vs (b).

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

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

$\Rightarrow$ Just about any perturbation $\gg \Delta\epsilon \Rightarrow$ 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

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

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

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

$$\hat{H}_{S-E} = \hat{\sigma}_z \sum_\alpha \; \underset{\alpha}{C}\, \hat{x}_\alpha \leftarrow \text{ oscillator coords.}$$

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

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

$$\Downarrow$$

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

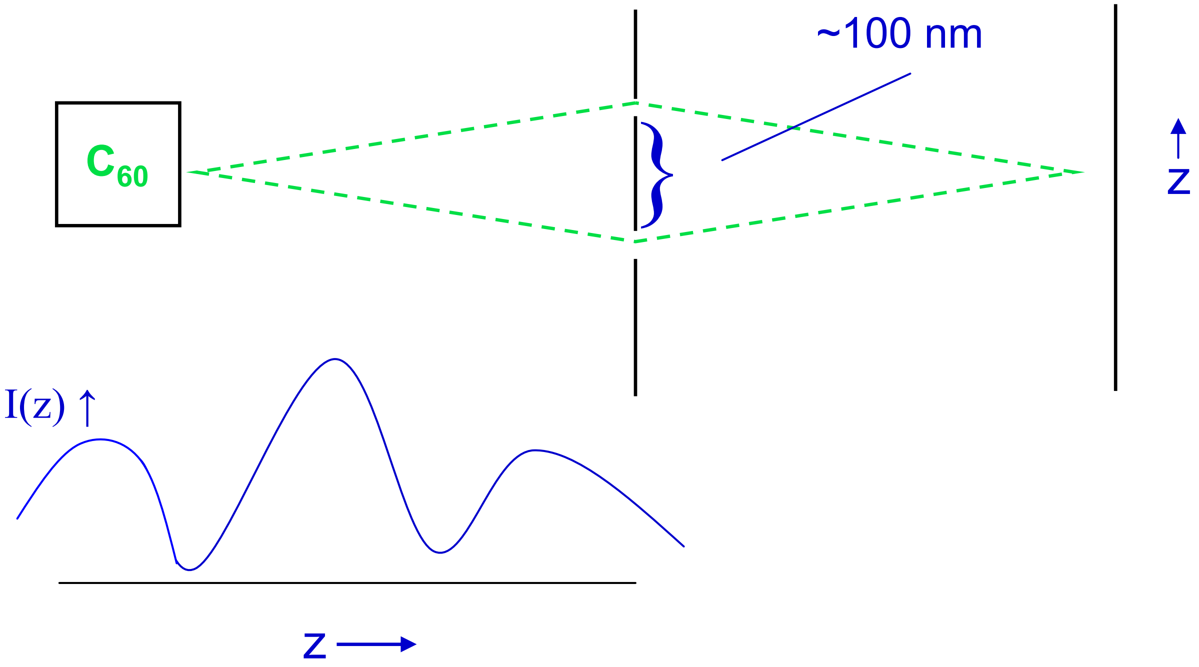
$$\langle \chi_+ | \chi_- \rangle = \exp - F \cong 0 \qquad \text{FC factor}$$

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

decohered?? (cf. neutron interferometer)

The Search for QIMDS

1.Molecular diffraction*



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

$$f(\upsilon) = A\upsilon^3 \exp-(\upsilon-\upsilon_o)^2/\upsilon_m^2 \qquad (\upsilon_o \sim 1{\cdot}8\,\upsilon_m)$$

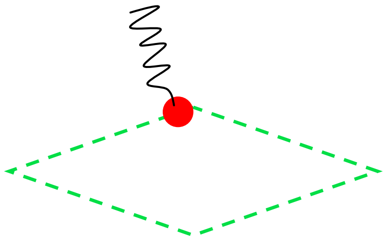
(b.) "Which-way" effects?

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?

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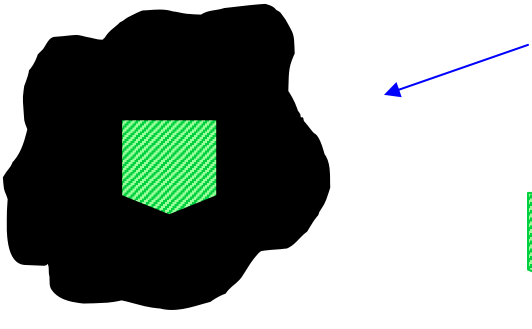
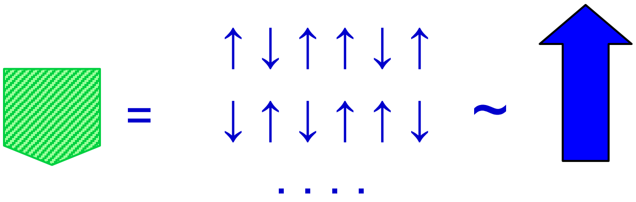
*Arndt et al., Nature *401*, 680 (1999); Nairz et al., Am. J. Phys. *71*, 319 (2003).

The Search for QIMDS (cont.)

2. Magnetic biomolecules*



Apoferritin sheath
(magnetically inert)



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

α|⬆⟩ + β|⬇⟩ ?

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

← (isotropic) exchange en.

no. of spins

uniaxial anisotropy

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

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

$$\ell n\ \omega_o \sim a - bN$$

← no. of spins, exptly. adjustable

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

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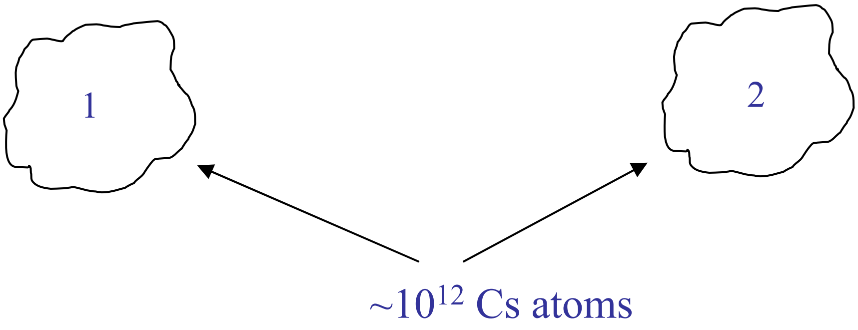
*S. Gider et al., Science *268*, 77 (1995).

The Search for QIMDS (cont.)

3. Quantum-optical systems*



for each sample separately, and also for total

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

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

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

$$\left\langle \delta J_{x\,tot} \delta J_{y\,tot} \right\rangle \geq | J_{z\,tot} |$$

so, if set up a situation s.t.

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

must have

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

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

but may have

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

(anal. of EPR)

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*B. Julsgaard et al., Nature *41*, 400 (2001); E. Polzik, Physics World *15*, 33 (2002)

Interpretation of idealized expt. of this type:

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

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

But,

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

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

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

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

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

but mixture will not give (#)

$\Rightarrow$ state must be of form

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

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

Note:

(a) QM used essentially in argument

(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)

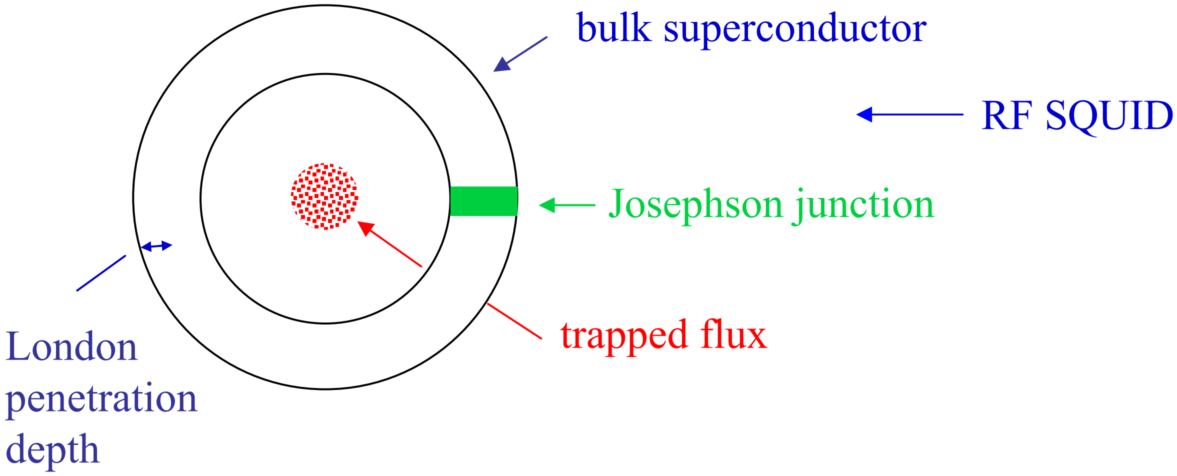
Advantages:

— classical dynamics of macrovariable v. well understood

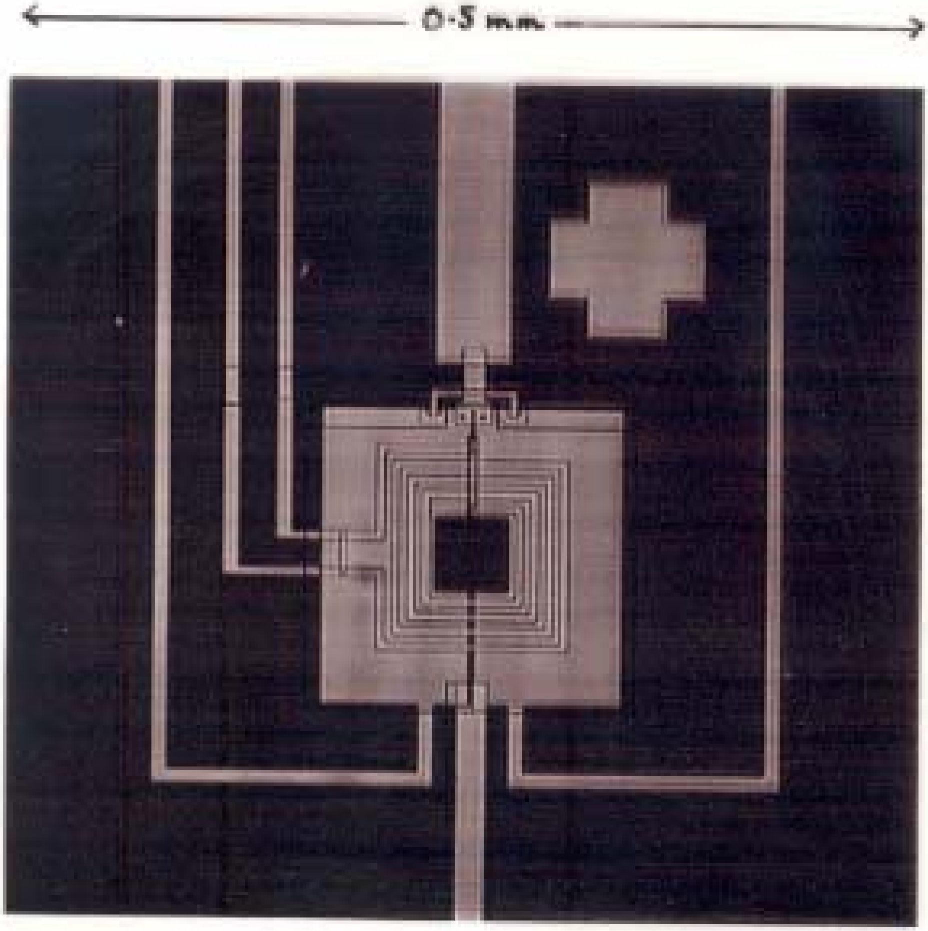
— intrinsic dissipation (can be made) v. low

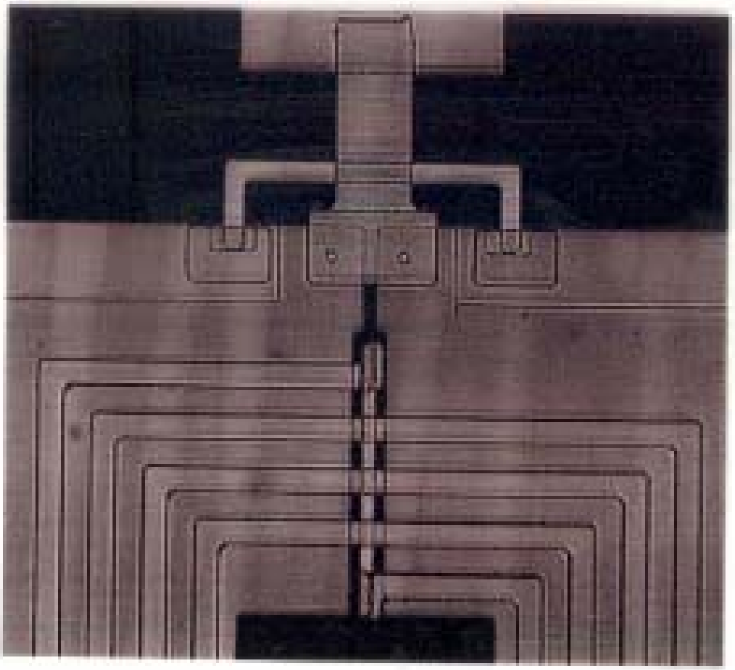
— well developed technology

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



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


0·5 mm



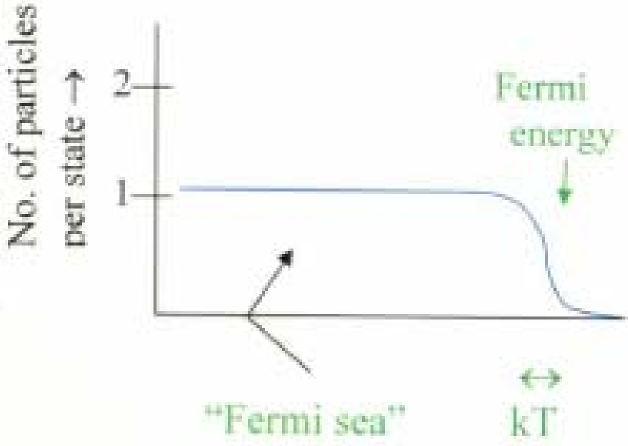
PHYSICS OF SUPERCONDUCTIVITY

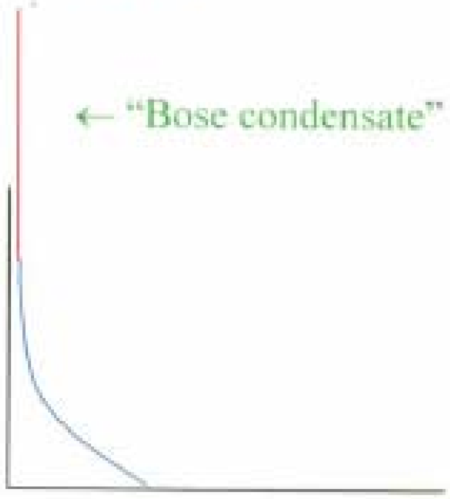
"Spin" of elementary particles $= \frac{n}{2}\hbar$

$0, 1, 2 \ldots.$ bosons

$\frac{1}{2}, \frac{3}{2}, \frac{5}{2} \ldots.$ fermions

At low temperatures:





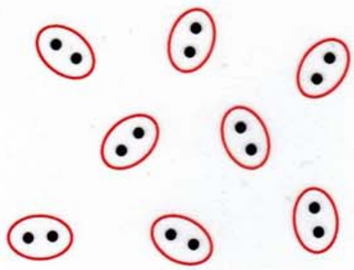
Electrons in metals: spin ½ ⇒ fermions

But a compound object consisting of an even no. of fermions has spin 0, 1, 2 … ⇒ boson.

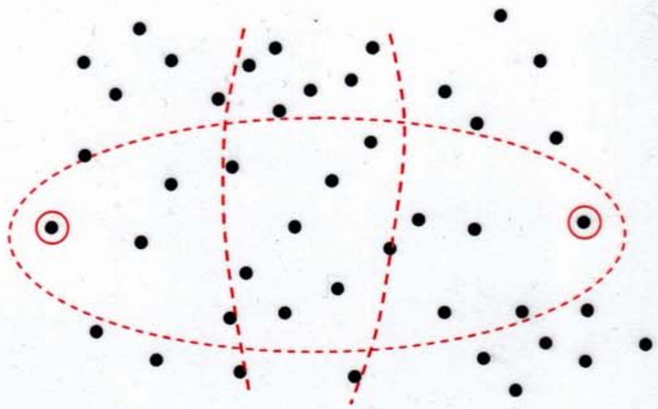
(Ex: $2p + 2n + 2e = {}^4He$ atom)

⇒ can undergo Bose condensation

Pairing of electrons:



“di-electronic molecules”

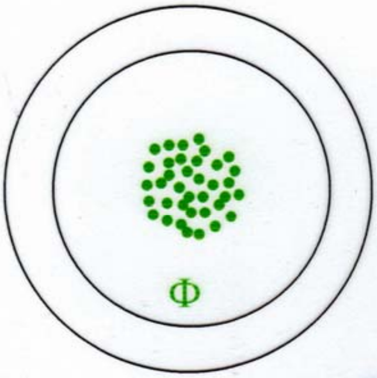


Cooper Pairs

In simplest (“BCS”) theory, Cooper pairs, once formed, must automatically undergo Bose condensation!

⇒ must all do exactly the same thing at the same time (also in nonequilibrium situation)

SUPERCONDUCTING RING IN EXTERNAL MAGNETIC FLUX:



Quantization condition for "particle" of charge 2e (Cooper pair):

$$K \equiv \oint \mathbf{v} \cdot \mathbf{dl} = \frac{h}{2m}\left(\overset{\text{integer}}{n} - \Phi/\underset{\text{“flux quantum” } h/2e}{\Phi_o}\right)$$

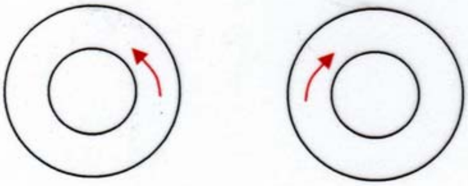
$$E \propto K^2$$

A. $\Phi = 0$: groundstate unique ($n = 0$)

$\Rightarrow$ all pairs at rest.

B. $\Phi = 1/2\ \Phi_o$: groundstate doubly degenerate

($n = 0$ or $n = 1$)



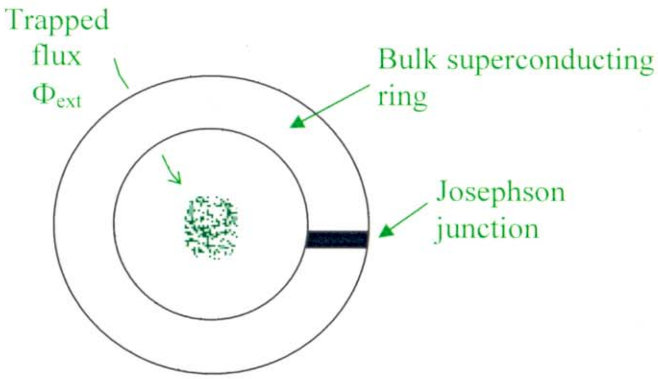
Either all pairs rotate clockwise

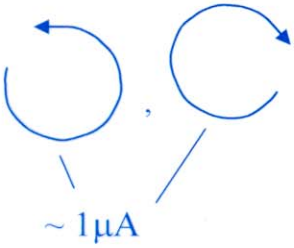
Or all pairs rotate anticlockwise

Note: state with 50% ↖ and 50% ↗

strongly forbidden by energy considerations

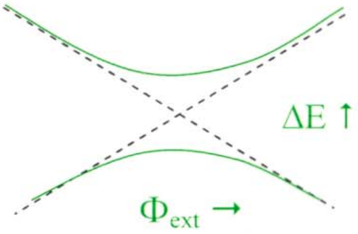
Josephson circuits





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

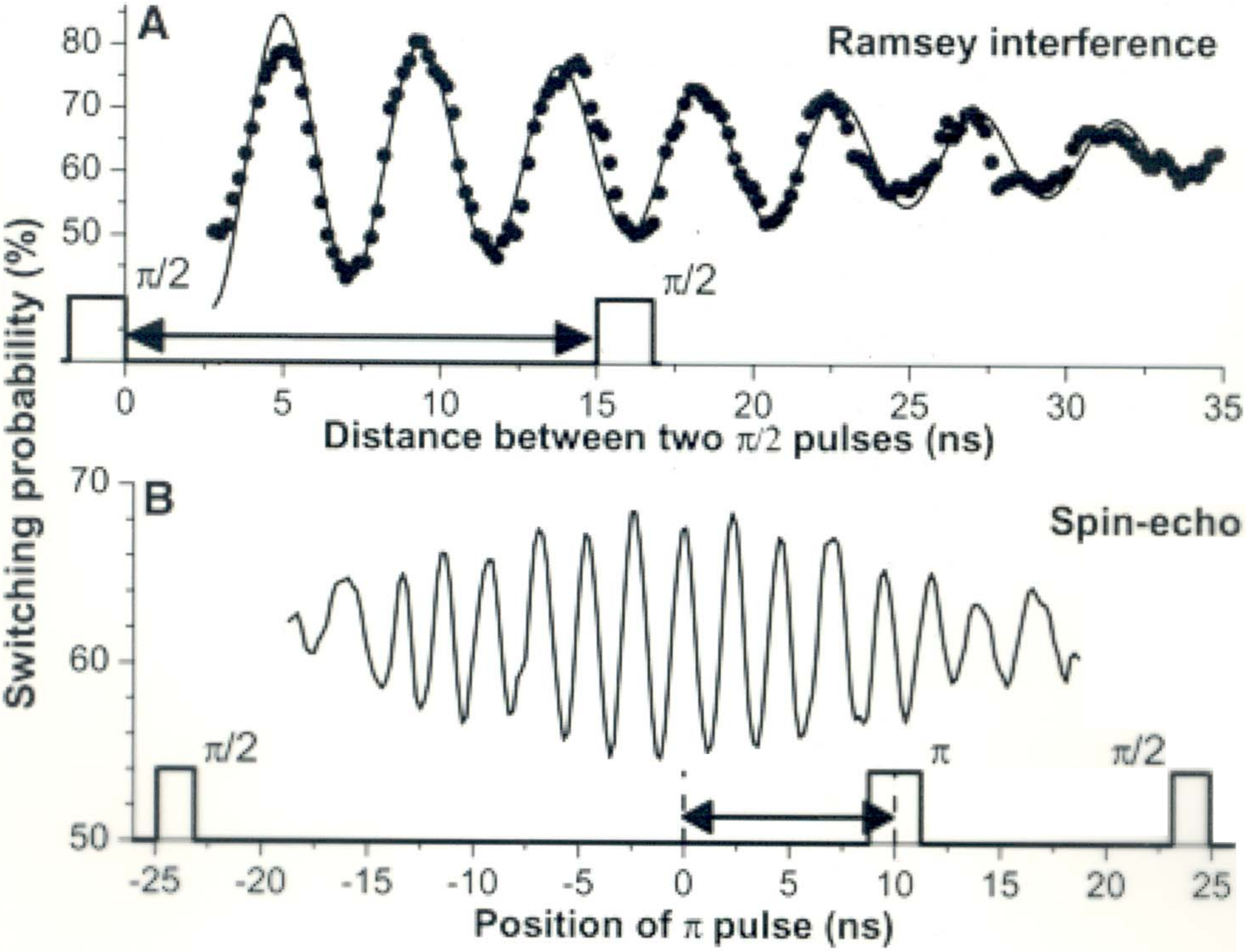
Evidence: (a) spectroscopic:
(SUNY, Delft 2000)



(b) real-time oscillations (like NH_3)

between $\circlearrowleft$ and $\circlearrowright$

(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)

WHAT IS THE DISCONNECTIVITY “D” (“SCHRÖDINGER’S-CATTINESS”) OF THE STATES OBSERVED IN QIMDS EXPERIMENTS?

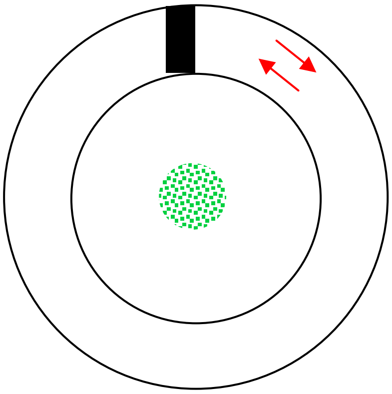
i.e., how many “microscopic” entities are “behaving differently” in the two branches of the superposition?

Fullerene (etc.) diffraction experiments: straightforward, number of “elementary” particles in C_{60} (etc.) (~1200)

Magnetic biomolecules: number of spins which reverse between the two branches (~5000)

Quantum-optical experiments
SQUIDS
} matter of definition

e.g. SQUIDS (SUNY experiment):



(a) naïve approach:

no. of C. pairs

$$\Psi_{\curvearrowright} \sim \chi_{\curvearrowright}^{N/2}, \quad \Psi_{\circlearrowleft} = \chi_{\circlearrowleft}^{N/2}$$

mutually orthogonal C. pair w.f.

$$\Rightarrow D \sim N \sim 10^9 - 10^{10}$$

⚠: Fermi statistics!

(b) how many single electrons do we need to displace in momentum space to get from $\Psi_{\curvearrowright}$ to $\Psi_{\circlearrowleft}$? (Korsbakken et al., preprint, Nov. 08)

$$\Rightarrow D \sim N(\upsilon_s / \upsilon_F) \sim 10^3 - 10^4$$

⚠: intuitively, severe underestimate in “BEC” limit (e.g. Fermi alkali gas)

(c) macroscopic eigenvalue of 2-particle density matrix (corresponding to (fairly) orthogonal states in 2 branches):

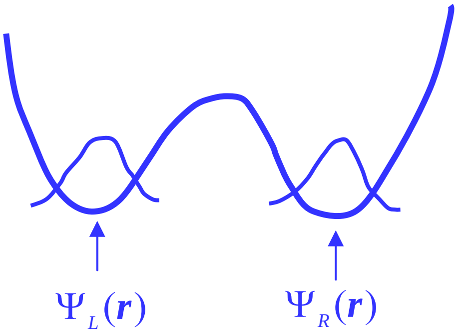
$$\Rightarrow D \sim N(\Delta / \varepsilon_F) \sim 10^6 - 10^7$$

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	$\sim 10^{19}$	(10^3–10^{15})
Cat	$\sim 10^{34}$	$\sim 10^{25}$

More possibilities for QIMDS:

(a) BEC's of ultracold alkali gases:

Bose-Einstein condensates



(Gross-Pitaevskii)

Ordinary GP state:

$$\Psi_N = \left(a\psi_L(\boldsymbol{r}) + b\psi_R(\boldsymbol{r})\right)^N$$

"Schrödinger-cat" state (favored if interactions attractive):

$$\Psi_N = a\left(\psi_L(\boldsymbol{r})\right)^N + b\left(\psi_R(\boldsymbol{r})\right)^N$$

problems:

(a) extremely sensitive to well asymmetry ΔE
(energy stabilizing arg (a/b) ~t^N ~ exp – NB/ℏ)

so ΔE needs to be
exp'ly small in N

single-particle tunnelling
matrix element

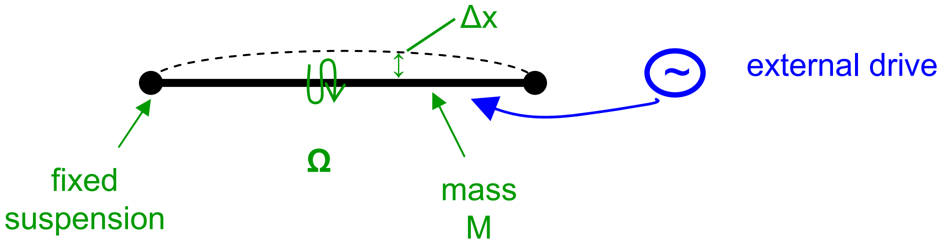
(b) detection: tomography unviable for N»1,
⇒ need to do time-sequence experiments (as in SQUIDS), but period v. sensitive e.g. to exact value of N

More possibilities for QIMDS (cont):

(b) MEMS

micro-electromechanical systems

Naïve picture:



$M \sim 10^{-18}$ kg (NEMS)

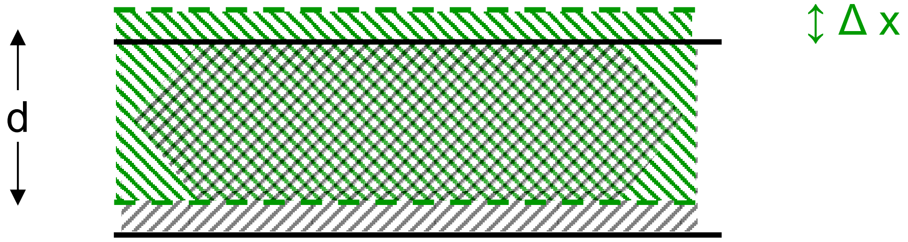
$\sim 10^{-21}$ kg (C nanotube)

$\Omega \sim 2\pi \cdot 10^{8}$ Hz

$\Rightarrow T_{eq} \equiv \hbar\,\Omega / k_B \sim 5$ mK , $\underset{\uparrow}{x_0} \sim 10^{-12}$ m

rms groundstate displacement

Actually:



In practice, Δx « d.

⚠: Problem: simple harmonic oscillator!
(One) solution: couple to strongly nonlinear microscopic system, e.g. trapped ion. (Wineland)

Can we test GRWP/Penrose dynamical reduction theories?

WHAT HAVE WE SEEN SO FAR?

1. If we interpret raw data in QM terms, then can conclude we have a quantum superposition rather than a mixture of meso/macroscopically distinct states.

   However, "only 1 degree of freedom involved."

2. Do data exclude general hypothesis of macrorealism?
   NO

3. Do data exclude specific macrorealistic theories?
   e.g. GRWP ← Ghirardi, Rimini, Weber, Pearle

   NO (fullerene diffraction: N not large enough, SQUIDS: no displacement of COM between branches)

   Would MEMS experiments (if in agreement with QM) exclude GRWP?

   alas: $\Gamma_{coll} \propto \Delta x, \qquad \Gamma_{dec} \propto (\Delta x)^2$

   collapse rate
   in GRWP theory

   decoherence rate
   acc. to QM

   ⇒ do not gain by going to larger Δx
   (and small Δx may not be enough to test GRWP)

HOW CONFIDENT ARE WE ABOUT (STANDARD QM'I) DECOHERENCE RATE?

Theory:

(a) model environment by oscillator bath (may be questionable)

(b) Eliminate environment by standard Feynman-Vernon type calculation (seems foolproof)

Result (for SHO):

$$\Gamma_{dec} \sim \Gamma\left(\frac{k_B T}{\hbar\Omega}\right)\cdot\left(\frac{\Delta x}{x_0}\right)^2$$

provided $k_B T » \hbar\Omega$

energy relaxation rate (Ω/Q)

zero-point rms displacement

ARE WE SURE THIS IS RIGHT?

Tested (to an extent) in cavity QED: never tested (?) on MEMS.

Fairly urgent priority!

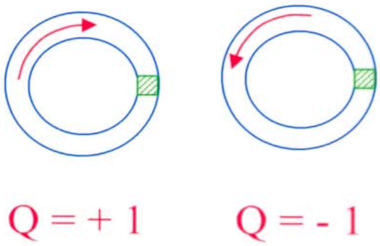
Where do we go from here?

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) $\forall$ t,

whether or not observed.

II. Noninvasive measurability

III. Induction

Can test with existing SQUID Qubits!

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*S. Aaronson, STOC 2004, p. 118.

Df:

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

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

Then,

(a) Any macrorealistic theory:	K≤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: ? !