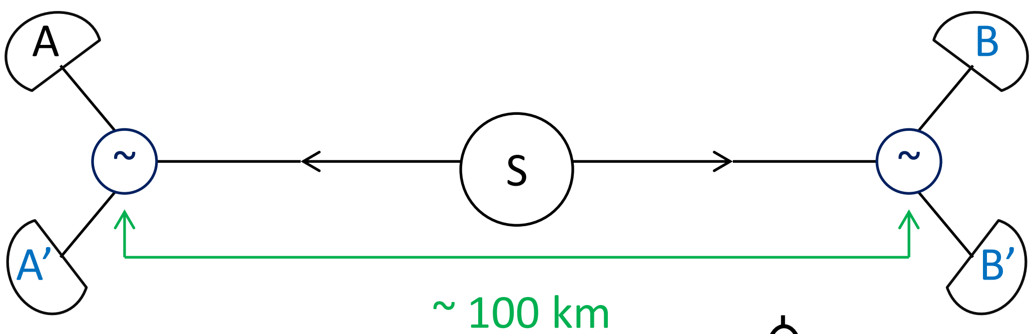
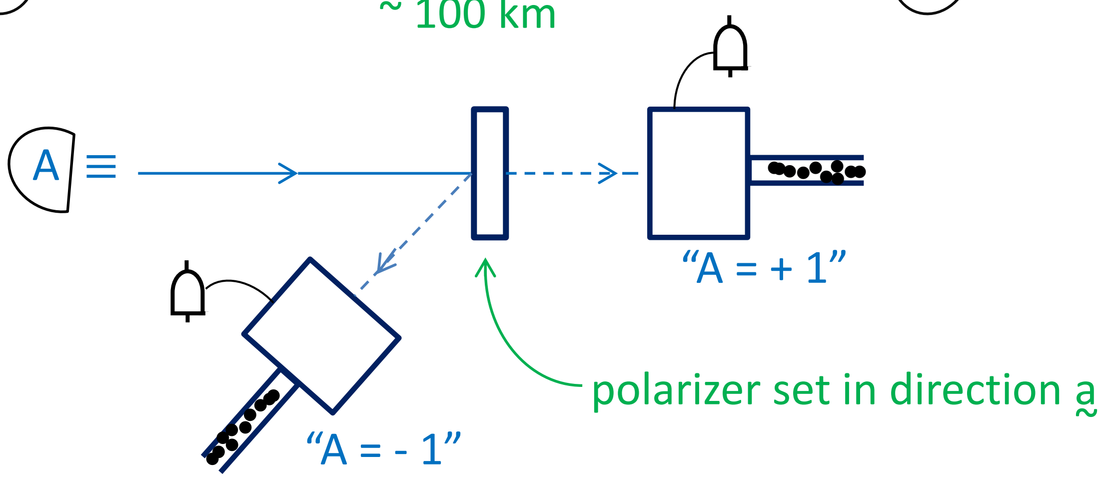
ON THE STRUCTURE OF A WORLD (WHICH MAY BE) DESCRIBED BY QUANTUM MECHANICS.

A. WHAT DO WE KNOW ON THE BASIS OF ALREADY PERFORMED EXPERIMENTS?





CHSH inequality:

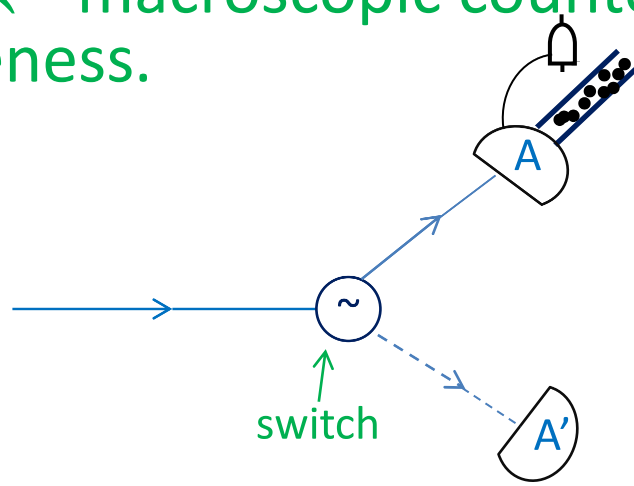
$$\langle AB\rangle + \langle A'B\rangle + \langle AB'\rangle - \langle A'B'\rangle \leq 2$$

violated by predictions of QM, and
by experiment!

WHAT DOES EXPERIMENTAL VIOLATION OF CHSH INEQUALITY IMPLY?

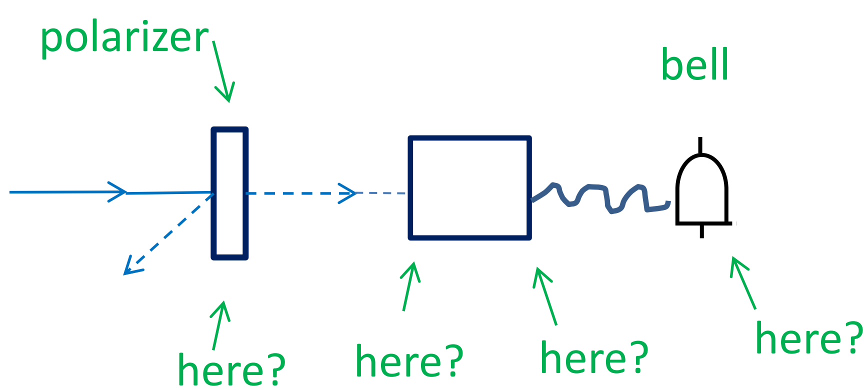
Must reject (at least) one of

1. Einstein locality
2. Induction
3. MCFD ← macroscopic counterfactual definiteness.



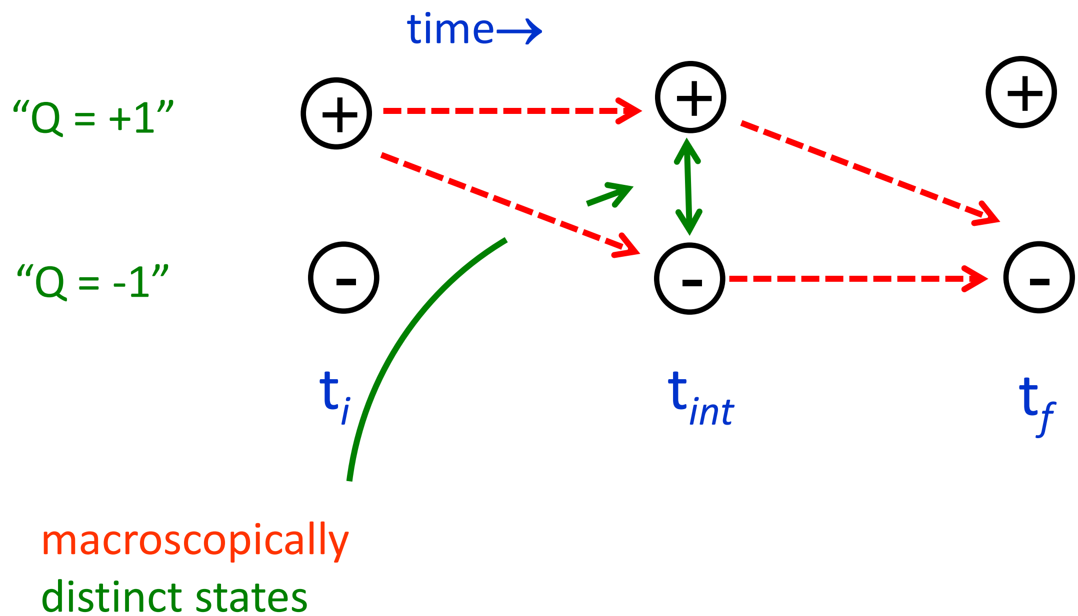
Had photon been switched into A' rather than A. A would not have been definite. But in actuality, A is definite. (bell rings, computer prints out...). So:

at which point did A become definite?

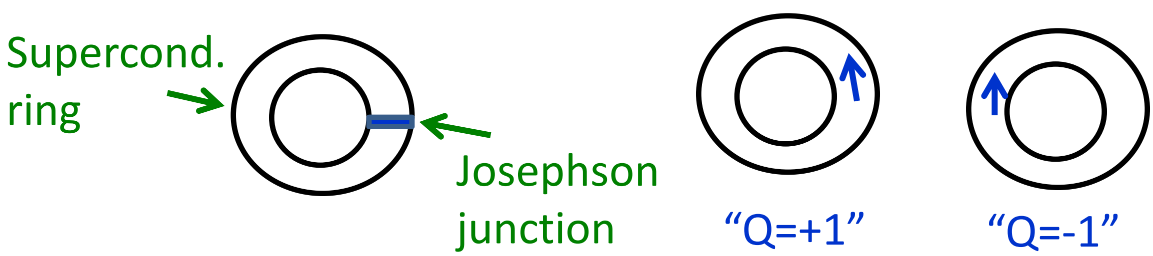


("SCHRODINGER'S CAT!)

MACROSCOPIC QUANTUM COHERENCE (MQC)



Example: "flux qubit":



Existing experiments: if raw data interpreted in QM terms, state at t_{int} is quantum superposition (not mixture!) of states ⊕ and ⊖.

↑: how "macroscopically" distinct?

Analog of CHSH theorem for MQC:
Any macrorealistic theory satisfies constraint

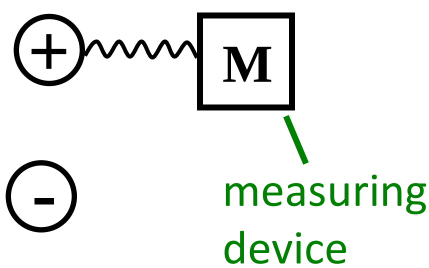
$$\langle Q(t_1)Q(t_2)\rangle + \langle Q(t_2)\, Q(t_3)\rangle + \langle Q(t_3)Q(t_4)\rangle - \langle Q(t_1)Q(t_4)\rangle \leq 2$$

which is violated (for appropriate choices of the t_i) by the QM predictions for an "ideal" 2-state system

Definition of "macrorealistic" theory: conjunction of

1) induction
2) macrorealism ($Q(t) = +1$ or -1 for all t)
3) noninvasive measurability (NIM)

NIM:



If Q = +1, throw away
If Q = -1, keep

In this case, unnatural to assert 3) while denying 2).
NIM cannot be explicitly tested, but can make "plausible" by ancillary experiment to test whether, when Q(t) is known to be (e.g.) +1, a noninvasive measurement does or does not affect subsequent statistics. But measurements must be projective ("von Neumann").

"ALL ELECTRONIC" SUPERCONDUCTIVITY
(heavy fermions, organics, cuprates, ferropnictides...)

WHERE IS THE ENERGY SAVED?

Consider "strongly layered" (2D) materials

(organics, cuprates, ferropnictides, $Sr_2Ru\,O_4$...)

assume:

1. Phonons irrelevant to first approximation
2. inter-unit-cell motion irrelevant to first approximation (c-axis)

Then:

$$\hat{H} = \hat{T}_{\parallel} + \hat{U} + \hat{V}$$

- $\hat{T}_{\parallel}$: in-plane KE
- $\hat{U}$: lattice potential
- $\hat{V}$: inter-conduction electron Coulomb interaction

Which of these is saved in N$\rightarrow$ S transition?

Default option: $\langle V \rangle$ (assume for sake of argument)

Rigorous theorem (not RPA!):

$$\langle V \rangle = \sum_q \int \frac{d\omega}{2\pi} \, \mathrm{Im} \left\{ \frac{1}{1 + V_q \chi_o(q\omega)} \right\}$$

- V_q: in-plane FT of Coulomb interaction
- $\chi_o(q\omega)$: "bare" density response function

So, obvious question:

where in space of q and ω is Coulomb energy saved (or not)?

"Ideal" experimental technique: transmission EELS

(P. Abbamonte, J. Zuo (University of Illinois) (reflection))

CONJECTURE:

(MUCH OF) COULOMB ENERGY SAVED IN REGIME OF SMALL **q** $\left(q \lesssim 0.3\text{Å}^{-1}\right)$ AND MIDINFRARED ω $(0.1 \lesssim \omega \lesssim 3-4\ eV)$

If that's true, may have implications for optics, as well as EELS.

Assume (for sake of argument): for $q \lesssim 0.3\text{Å}^{-1}$, $\omega \gtrsim 0.1$ eV

1) $\varepsilon_{\perp}(q\omega) \cong \varepsilon_{\parallel}(q\omega)$

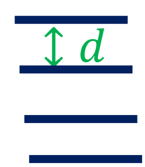
2) $\varepsilon_{\parallel}(q\omega)$ not strongly dependent on q

3D dielectric constant

Then:

optics measures $\varepsilon(\omega)$

Coulomb energy $\propto -\mathrm{Im}\left\{\frac{1}{1+q\frac{d}{2}(\epsilon(\omega)-1)}\right\}$



Note: for "jellium" model $\left(\varepsilon(\omega) \sim 1-\omega_p^2\ /\ \omega^2\right)$

expect crossing of $\mathrm{Re}\,\varepsilon$ at ω_p, but main contribution to Coulomb energy from

$$\omega \sim \omega_q \equiv \left(\frac{qd}{2}\right)^{1/2} \omega_p > \omega_p \left(\frac{\omega_q}{\omega_p} \sim 2 \cdot 2 \text{ for Bi–2212}\right)$$

hence, not so strange that anomalies in optics for $N \rightarrow S$ occur not around $\omega_p(\sim 1 \cdot 2\ eV)$ but around $\sim 2 \cdot 5 - 3$ eV!

More quantitatively:

if conjecture is correct, what (qualitatively) do we expect to happen in optics for N →S, for $\omega \lesssim \omega_q$?

crucial observation*: for $0.1 \text{ eV} \lesssim \omega \lesssim 1\text{eV}$, in Bi-2212

$$\varepsilon(\omega) \cong (-1+i)\ \omega_p^2/\omega^2$$

i.e.

$$\arg \varepsilon \sim 3\pi/4$$

Now, in this regime,

$$\Delta\langle V\rangle \sim -\Delta(\mathrm{Im}\,\varepsilon^{-1}) \sim \mathrm{Im}\,(\Delta\varepsilon/\varepsilon^2)$$

but $\varepsilon^{-2} \sim \mathrm{i}/2$, so

$$\Delta\langle V\rangle \sim \Delta(\mathrm{Re}\ \varepsilon)$$

Thus, expect in this regime

(Im ε irrelevant), Re ε decreases

seen in experiments both in Bi-2212 and in 122!

*El-Azrak et al., Phys. Rev. B 49, 9846 (1994)

SUPERFLUIDITY AND "SUPERSOLIDITY": THE TOPOLOGY OF MANY-BODY WAVE FUNCTIONS

(some problems just don't go away)

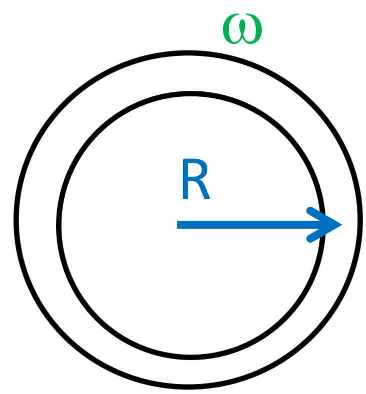
Classic problem: system of neutral atoms (e.g. ^{4}He)

$(\omega \ll \omega_c \equiv \hbar^2 \mathrm{m} R^{2)}$

Classically. $\Delta \boldsymbol{L} = I_{el}\boldsymbol{\omega}$

↖

$\approx NmR^2$



for quantum gas. $k_B T \gg \hbar\omega_c$: Same

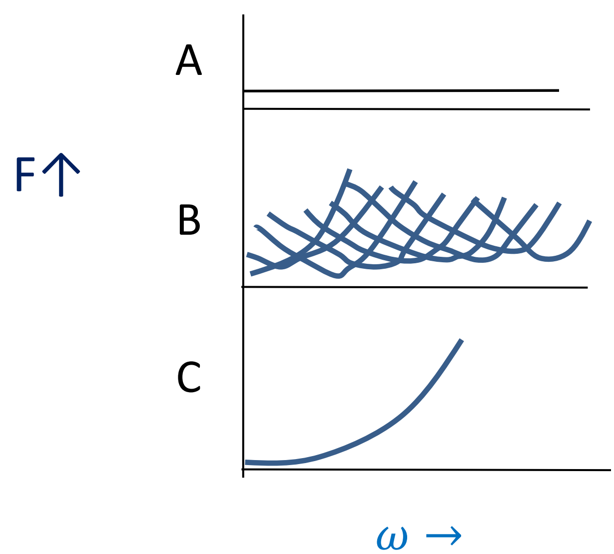
QM'l system with interaction?

Kohn (1964): consider

F as f(ω)

↑

Free Energy



A: Insulator

Rotates with annulus

(no hysteresis)

B: Normal liquid

Rotates with annulus

(but with hysteresis)

C: Superfluid

does not rotate with annulus.*

How to characterize behavior A-C in terms of topology of MBWF of system?

*will take this (not persistent currents !) as definition of superfluidity

Topology of MBWF'S: ODLRO (Yang.1962)

Boson system:

ODLRO if $\langle \psi(\mathrm{r})\psi^{+}(\mathrm{r}')\rangle \nrightarrow 0$ for $|\mathbf{r} - \boldsymbol{r}^{\mathbf{1}}| \rightarrow \infty$

General argument that ODLRO is a sufficient condition for superfluidity*. But, $64K question:

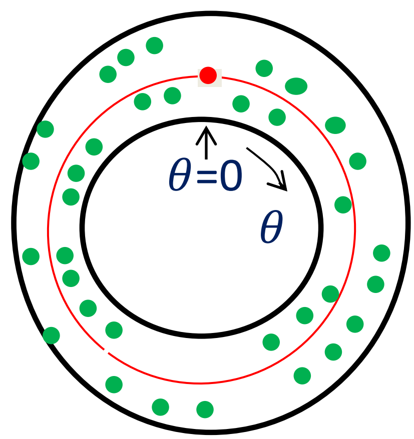
is it a necessary condition?

To evaluate F(ω), must decide how system responds to SVBC: ← single-valuedness boundary condition.

$$\text{For } \omega = 0, \Psi(\theta_1\theta_2 \ldots \theta_i \ \ldots \theta_N)$$
$$= \Psi(\theta_1\theta_2 \ldots \theta_i + 2_r \ldots \theta_N)$$

For $\omega \neq 0$.

$$\Psi(\theta_1\theta_2 \ldots \theta_i \ldots \theta_N) =$$



$$\exp 2\pi i \left(\frac{\omega}{\omega_c}\right) \Psi(\theta_1\theta_2 \ldots \theta_i + 2\pi \ldots \theta_N)$$

$64K question: Does adaptation to changed SVBC cost a free energy $\alpha\ \omega^2$?

If for all possible path: $\theta_i \rightarrow \theta_i + 2\pi$ (including "Japanese- bus" paths) MBWF goes to zero exponentially somewhere on path, can modify SVBC at no cost in ω (case of insulator)

But lack of ODLRO says only that this is true for "British-bus" paths. ($\theta_1\theta_{2\ldots}$fixed).....

*Noninteracting Bose gas is not a counter example!

(cf. df. of "superfluidity")

THE LOW-TEMPERATURE PROPERTIES OF GLASSES: THE "CINDERELLA PROBLEM" OF CONDENSED MATTER PHYSIES

The problem in a nutshell: below 1 K, the properties of amorphous materials ("glasses") are not only qualitatively but quantitatively universal.

E.g. Dimensionless absorption Q_t^{-1} of transverse ultrasound in GHz range *. For almost all† amorphous materials.

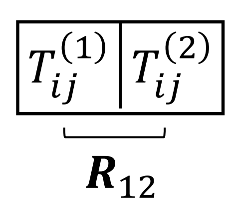
$$\boxed{Q_t^{-1} = 3 \times 10^{-4} \pm \sim 25\%} \qquad \equiv Q_o^{-1}$$

In "standard" (TTLS) ⟵ tunneling 2-level systems

model of glasses. Q_t^{-1} is product of 4 independent faston, each of which fluctuates by ~ 5-10. And yet…

Generic model: $\hat{H}' = \sum_{ij} e_{ij} T_{ij}$ (phonon strain: e_{ij}; generic stress: T_{ij})

$$\Longrightarrow \hat{H}_{eff} \sim \sum_{nm} (\text{4th–order polynomial in } \boldsymbol{n}_{nm})$$



$$\times \frac{T_{ij}^{(m)} T_{kl}^{(n)}}{R_{nm}^3} \longrightarrow$$ real–space renormalization procedure

*mostly inferred by KK from T-dependent velocity shift

† for a very few materials, less than this: never greater.