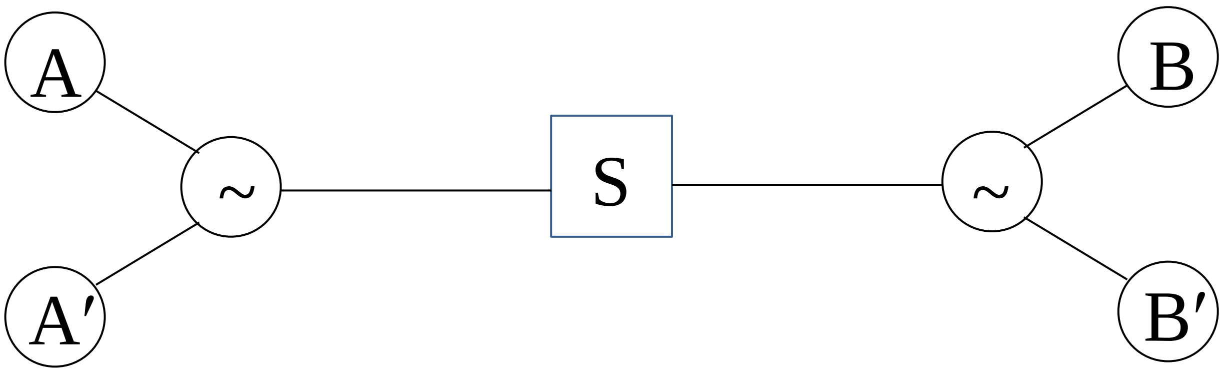
MACROREALISM and "WEAK MEASUREMENT"

Original CHSH inequality:

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



($A, B, A', B' = \pm 1$)
Satisfied by all objective local theories, df. by conjunction of

1) Induction
2) Einstein locality
3) (Micro) realism

What, exactly, do we mean by (micro) "realism"?
Possible definition in terms of macroscopic counterfactual definiteness
(MCFD):
Suppose a given photon (which was in fact switched into A′) had been switched into A. Then

i) "It is a fact that either counter A would have clicked ($A = +1$) or it would not have clicked ($A = -1$)" ←truism?
ii) "Either it is a fact that $A = +1$ or it is a fact that $A = -1$"

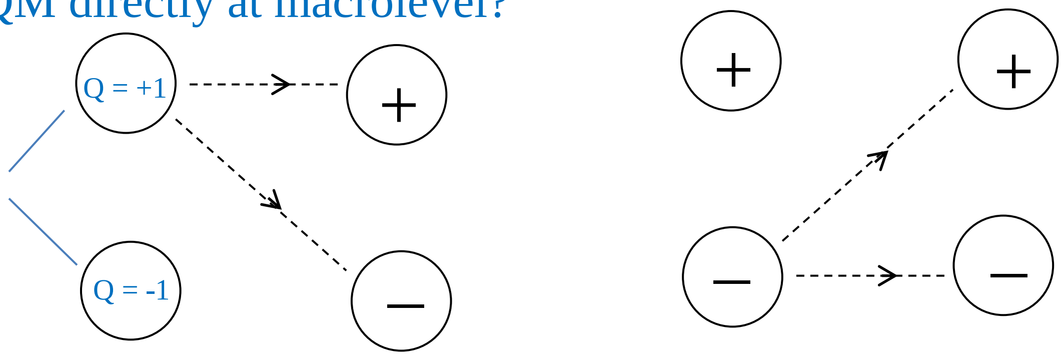
↑
MCFD

Do counterfactuals have truth values? (common sense, legal system…assume so!)

Possible loophole in EPR-Bell expts: "collapse locality" (at what stage is a definite outcome realized? - if never, get Schrödinger's cat!)

Can we test QM directly at macrolevel?

macroscopically distinct states



$P_+ \neq 0$ $P_- \neq 0$

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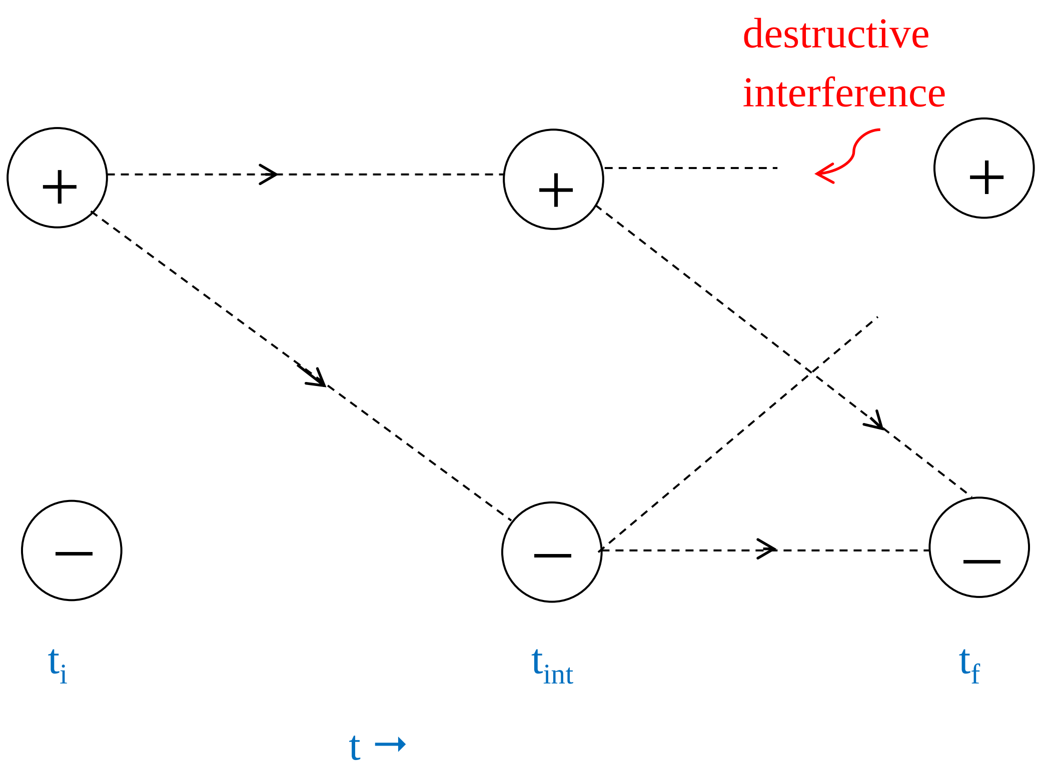


What is correct description at t_{int}?

If state is <u>either</u> + <u>or</u> − (classical mixture) then inevitably, at t_f, $P_+ \neq 0$, $P_- \neq 0$. But QM says:

$$P_+(t_f) = 0, \; P_-(t_f) = 1 \quad !$$

Can we make argument more quantitative?

"CHSH inequality in time":

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

Note ensemble averages (repeated runs, with measurements <u>only</u> at specified pairs of times)

Can actually take $t_3 = t_4$ without loss, hence

$$K(t_1 t_2 t_3) \equiv \langle Q(t_1)Q(t_2)\rangle + \langle Q(t_2)\, Q(t_2)\rangle - \langle Q(t_1)\, Q(t_3)\rangle \le 1 \ (*)$$

[Boole, 1862]

QM prediction for ideal 2-state system with tunnelling amplitude ω_o

$$\langle Q(t_i)\, Q(t_j)\rangle = \cos\{\omega_o(t_i - t_j)\}$$

so if $t_3 - t_2 = t_2 - t_1 = \tau$.

$$K(\tau) = 2\,\cos\,\omega_o\tau - \cos(2\omega_o\tau)$$

violates (*) for some τ, maximally at $\tau = \frac{\pi}{3\omega_o} (K(\tau) = 1\cdot 5)$

What ingredients do we need to prove (*)?

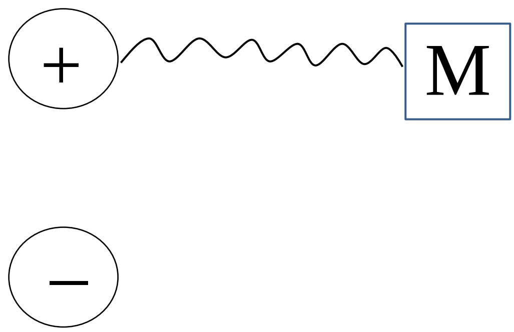
1) induction
2) macrorealism

Macrorealism: "at all times, either Q = +1 or Q = -1": but what does this actually mean, if Q is not observed? In last resort, must again define in terms of MCFD (but goes beyond EPR-Bell, in that "choice" of whether to observe or not postponed to macroscopic level)

1) and 2) alone do not permit derivation of (*), because measurement at first time of pair t_i, t_j could have affected ensemble. Hence must add…

3) Noninvasive measurability "in principle, possible to measure $Q(t)$ without affecting state of ensemble or subsequent behavior"
(note NOT a QM'l principle!)

Made plausible by idea of ideal negative result (INR) measurement:



If M clicks, throw away that run. If M does not click, keep result, argue that since on that run system "is not" in +, it must "be" in – (macrorealism!) and thus could not have been affected by presence of M. Then switch + $\rightleftarrows$ – and thereby obtain complete statistics.

Partial "experimental justification" of NIM:

1) prepare system in given state at time t_i, choose t_{int} so that QM unambiguously predicts (say) $Q(t_{int}) = -1$.

2) Verify experimentally that $Q(t_{int}) = -1$. (i.e. that M does not click)

3) Measure $Q(t_f)$ in series of runs in which no measurement is made at t_{int}.

4) Measure $Q(t_f)$ in series of runs in which an INR measurement (as above) is made at t_{int}.

5) Compare statistics of runs (3) and (4). If they agree, consistent with NIM.

Proof of (*) from (1) + (2) + (3), assuming measurements are INR:

1. From (2), either $Q(t_i) = +1$ or $Q(t_i) = -1$ ("either M would have clicked, or M would not have clicked")

2. By simple algebra, on any given run,
   $Q(t_1)Q(t_2) + Q(t_2)Q(t_3) - Q(t_1)Q(t_3) \leq 1$

3. Hence for any single ensemble ("ens")
   $\langle Q(t_1)Q(t_2)\rangle_{ens} + \langle Q(t_2)Q(t_3)\rangle_{ens} - \langle Q(t_1)Q(t_3)\rangle_{ens} \leq 1$

4. By (1) and (3), ensembles on which (INR) measurements are made at different pairs of times are identical.

5. Hence can replace $\langle Q(t_i)Q(t_j)\rangle_{ens}$ by $\langle Q(t_i)Q(t_j)\rangle_{ij}$
   ($\langle A\rangle_{ij} \equiv$ av. on runs on which measurements made at t_i, t_j (only)) $\Rightarrow$ (*), QED

Note: whole idea of macrorealism (macroscopic CFD) implies that "clicked" and "non-clicked" states of M are distinguishable (orthogonal), i.e. that measurements are projective ("v.N")

Such a measurement scheme recently used by Knee et.al. (arXiv: 1104.0238) to test realism at microscopic level (nuclear spins) (it fails!)

But, for macroscopic systems (e.g. superconducting qubits), v.N. measurements usually very difficult.

Thus, question raised by Ruskov et.al. (PRL **96**, 200 404 (2006)):

Can we test macrorealism with "weak" measurements?

Answer given: yes

Expt.: Palacios-Laloy et.al., Nature Physics **6**, 442 (2010)

[will not discuss "degree of macroscopicness"]

Weak "measurement"*

v.N: $\chi_i \Phi_o \longrightarrow \chi_i \Phi_i$ $\quad (\Phi_i, \Phi_i) = \delta_{ij}$

S M $\quad \hat{H}_{S+M}$

can be achieved e.g. by

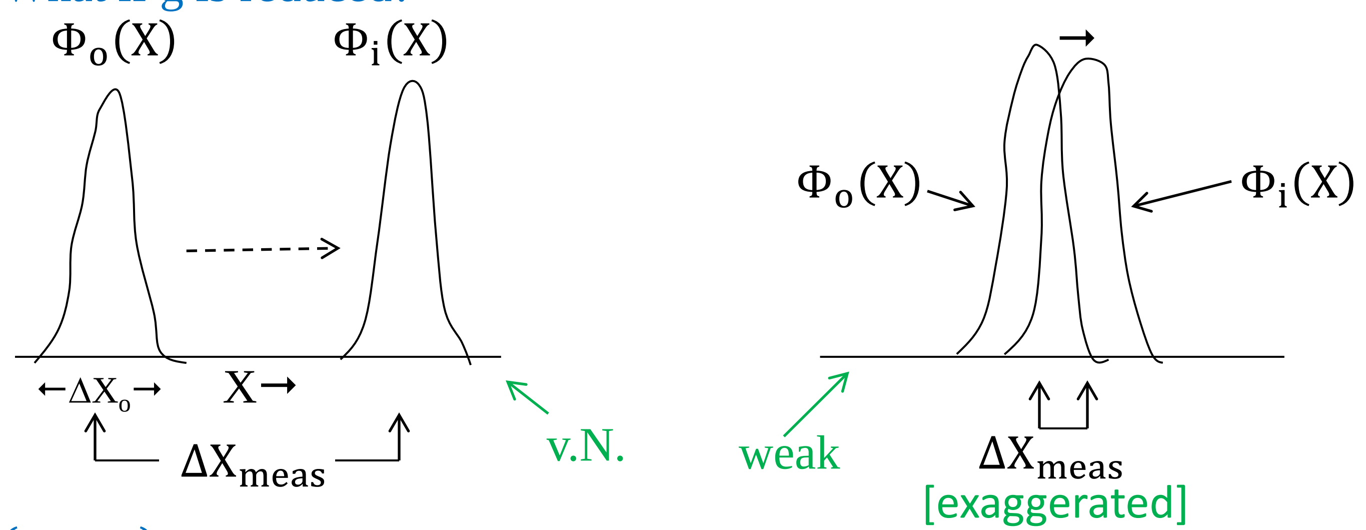
momentum conjugate to coordinates X of M

$$\widehat{H}_{S+M} = g a_i \hat{P} \delta(t)$$

Eigenvalue of λ in state X_i

provided $g|a_i - a_j| \gg \Delta X_o \leftarrow$ zero-point spread of $\Phi_o(X)$

What if g is reduced?



$(\Phi_i, \Phi_j) \sim (\Phi_i, \Phi_o) \cong 0$ $\quad (\Phi_i, \Phi_j) \sim (\Phi_i, \Phi_o) \sim 1 - \epsilon \ (\epsilon \ll 1)$

V. little information acquired from single measurement. But can e.g. couple to M continuously and use Bayesian inference to extract information about S.

Ruskov et.al.: monitor state of qubit weakly but continuously $\Rightarrow$ time correlations of M should reflect those of S.

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*Aharonov et. al., PRL **60**, 1351 (1988) ("postselection" considerations not necessary in present context)

Model of Ruskov et.al. (applied by Palacios-Laloy et.al. to interpret their data):

2-state system S (e.g. superconducting qubit) coupled weakly but continuously to measuring device M (e.g. QPC). Response of M given by

quantum point contact

$$I(t) - I_o = (\Delta I/2)\, Q(t) + \xi(t) \leftarrow \text{noise}$$

"ideal" response

$$\langle \xi(t) \rangle = 0\,, \langle \xi(t_1)\xi(t_2) \rangle = \frac{1}{2}\, S_o\, \delta(t_1 - t_2) \leftarrow \text{"white noise"}$$

weak-coupling condition:

$$(\Delta I)^2/4S_o \ll \omega_o \longleftarrow \text{oscillation rate of qubit}$$

(i.e. M cannot efficiently detect state of S over one period of oscillation)

Claims:

(a) damping (decoherence) rate Γ of 2-state oscillations given by

$$\Gamma\ (\gamma +)\ (\Delta I)^2/4S_o$$

decoherence not associated with M

(so weak-coupling condition equivalent to $\Gamma \ll \omega_o$)

(b) both in QM and in MR, (but for different reasons!) output of detector, $q(t) \equiv (I(t) - I_o)/(\Delta I/2)$, has correlations $K_M(t_i, t_j) \equiv \langle q(t_i) q(t_j) \rangle$ which are identical to those of S.

(c) in MR theory, with assumption (2), (*) is satisfied.

(d) Therefore, an experimental observation of $K_M(\tau)$ which violates (*) refutes the class of MR theories.

Some comments on argument of Ruskov et.al.:

1. Since the detector output q(t) is itself continuously (+efficiently!) monitored, it cannot possibly itself violate (*). What an "apparent" violation (e.g. $2K_M(\tau) - K_M(2\tau) > 1$) indicates is simply that since

$$q(t) \equiv \frac{I(t)-I_o}{\Delta I/2} = \underset{\substack{\uparrow \\ \pm 1}}{Q(t)} + \frac{\xi(t)}{\Delta I/2}$$

the allowed range of q(t) is > (-1, +1)!

2. Thus, the crucial element in the argument is that for both QM and MR, the correlations $K_M(t_i, t_j)$ of M faithfully reflect the correlations $K(t_i, t_j)$ of S. The argument for this: in both QM and MR.

$$K_M(t, t+\tau) \equiv \left\langle \left(Q(t) + \frac{\xi(t)}{\Delta I/2} \right) \cdot \left(Q(t+\tau) + \frac{\xi(t+\tau)}{\Delta I/2} \right) \right\rangle$$

$$= \langle Q(t)Q(t+\tau)\rangle + (\Delta I/2)^{-1}\{\underbrace{\langle Q(t)\xi(t+\tau)\rangle}_{\text{vanishes by causality}} + \langle \xi(t)Q(t+\tau)\rangle\} + \left(\frac{\Delta I}{2}\right)^{-2} \underbrace{\langle \xi(t)\xi(t+\tau)\rangle}_{\substack{\text{vanishes for } \tau \neq 0 \\ \text{by white-noise} \\ \text{assumption}}}$$

$$= \langle Q(t)Q(t+\tau)\rangle + (\Delta I/2)^{-1} \langle \xi(t)Q(t+\tau)\rangle$$

Ruskov et.al. claim:

a) For QM, both terms nonzero and give (for $\Gamma \ll \omega_o$),

$$K_M(\tau) = \cos \omega\tau = K(\tau)$$

[but then unclear what df. of Q(t) is!]

b) In MR theory,

$$\langle \xi(t)Q(t+\tau)\rangle = 0 \qquad \Rightarrow K_M(\tau) = K(\tau)$$

("Since it is possible to make measurements without disturbing the system, there is no reason that any correlation has to arise between the noise that registers in the detector and the physical characteristic Q(t) of the system being measured")

3. Even in QM analysis, the relation

$$\Gamma = (\gamma +)\ (\Delta I)^2/4S_o$$

seems prima facie inconsistent with $\langle \xi(t)\xi(t+\tau)\rangle = \delta(\tau)$, since latter is a characteristic of classical (thermal) noise:

let ΔX_o $\equiv$ zero-point spread of X ← coordinate of M
ΔX_T $\equiv$ thermal spread of X
ΔX_M $\equiv$ displacement of mean value of X due to interaction with S.

Then distinguish:

i) efficient v. N. meast.: $\Delta X_M \gg \Delta X_O, \Delta X_T$
ii) inefficient v. N. meast.: $\Delta X_T \gg \Delta X_M \gg \Delta X_O$
iii) weak meast.: $\Delta X_O \gg \Delta X_M$ (ΔX_T any)

In iii), M does not decohere S. (much)

In i) M does (efficiently) decohere S

What about (ii)? This apparently involves decoherence without information. So, prime facie., in this case we should have

$$\Gamma = (\gamma +)(\Delta I)^2/4 \underset{\substack{\uparrow \\ \text{zero-point “noise”}}}{S_a} \gg (\gamma +)(\Delta I)^2/4S_O!$$