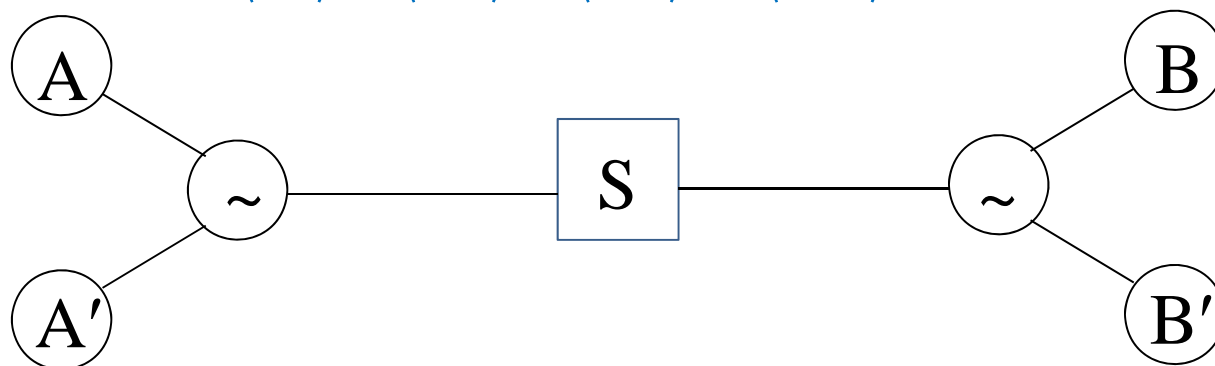


## MACROREALISM, NONINVASIVENESS and WEAK MEASUREMENT

For orientation, original CHSH inequality:

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



(A, B, A', B' = ±1)

Satisfied by all objective local theories, df. by conjunction of

- |   |   |  |
|---|---|--|
| <ol style="list-style-type: none"> <li>1) Induction</li> <li>2) Einstein locality</li> <li>3) (Micro) <b>realism</b></li> </ol> | } | <p>sufficient conditions, arguable<br/>whether necessary</p> |
|---|---|--|

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”

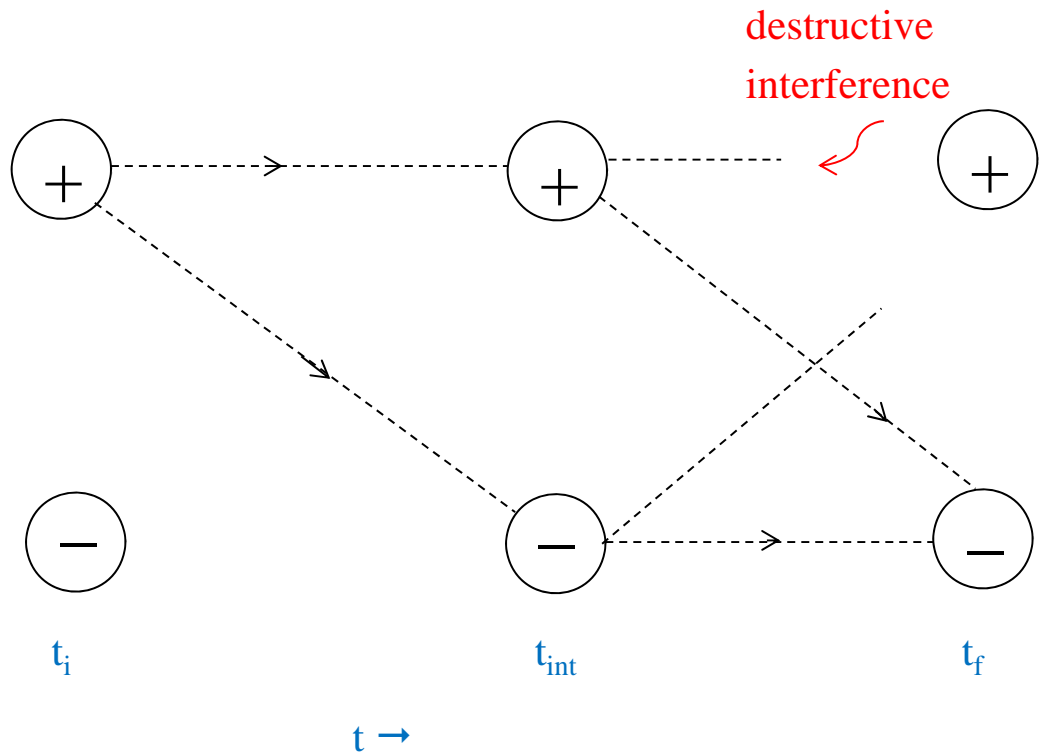
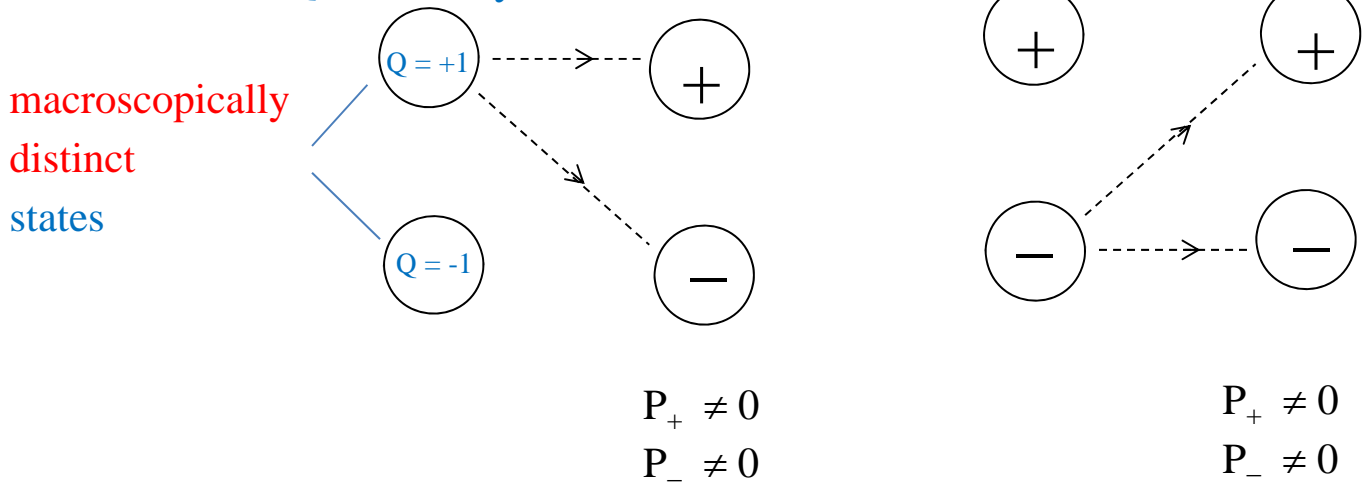


MCFD

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?



What is correct description at  $t_{int}$ ?

If state is either  $\oplus$  or  $\ominus$  (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”:

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

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

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

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

[Boole, 1862]

QM prediction for ideal 2-state system with tunnelling amplitude  $\omega_o$

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

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  $\tau$ , maximally at  $\tau = \frac{\pi}{3\omega_o}$  ( $K(\tau) = 1.5$ )

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What ingredients do we need to prove (\*)?

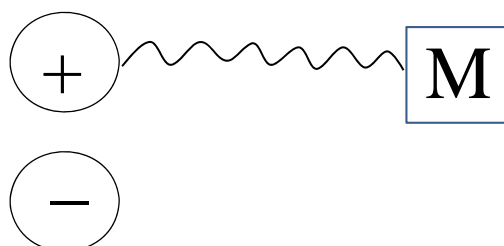
- 1) induction
- 2) **macrorealism**

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  $\oplus$ , it must “be” in  $\ominus$  (**macrorealism!**) and thus could not have been affected by presence of M. Then switch  $\oplus \rightleftharpoons \ominus$  and thereby obtain complete statistics.

Partial “experimental justification” of NIM (**test for “classical noninvasiveness”**)\*

- 1) prepare system in given state at time  $t_i$ , choose  $t_{\text{int}}$  so that QM unambiguously predicts (say)  $Q(t_{\text{int}}) = -1$ .
- 2) Verify experimentally that  $Q(t_{\text{int}}) = -1$ . (i.e. that M does not click)
- 3) Measure  $Q(t_f)$  in series of runs in which no measurement is made at  $t_{\text{int}}$ .
- 4) Measure  $Q(t_f)$  in series of runs in which an INR measurement (as above) is made at  $t_{\text{int}}$ .
- 5) Compare statistics of runs (3) and (4). If they agree, consistent with NIM.

\*cf. Wilde + Mizel, Found. Phys. 42, 256 (2012)

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”)  

$$\langle Q(t_1)Q(t_2) \rangle_{\text{ens}} + \langle Q(t_2)Q(t_3) \rangle_{\text{ens}} - \langle Q(t_1)Q(t_3) \rangle_{\text{ens}} \leq 1$$
4. By (1) and (3), ensembles on which (INR) measurements are made at different pairs of times are identical.
5. Hence can replace  $\langle Q(t_i)Q(t_j) \rangle_{\text{ens}}$  by  $\langle Q(t_i)Q(t_j) \rangle_{ij}$   
 $(\langle A \rangle_{ij} \equiv \text{av. on runs on which measurements made at } t_i, t_j \text{ (only)}) \Rightarrow (*)$ , 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. Nature Commun. 3, 606 (2012) to test realism at **microscopic** level (nuclear spins) (it fails!) (note: did not explicitly check for classical noninvasiveness).

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”]

\*see also Jordan et al., PRL **97**, 026805 (2006)



Model of Ruskov et.al. (applied by Palacios-Laloy et.al. to interpret their data): (note: postselection not explicitly involved\*)

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

$$I(t) - I_0 = (\Delta I/2) Q(t) + \xi(t) \leftarrow \text{noise}$$

“ideal” response

$$\langle \xi(t) \rangle = 0, \langle \xi(t_1) \xi(t_2) \rangle = \frac{1}{2} S_0 \delta(t_1 - t_2) \leftarrow \text{"white noise"}$$

weak-coupling condition:

$$(\Delta I)^2 / 4S_0 \ll \omega_0 \leftarrow \text{oscillation rate of qubit}$$

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

Claims:

(a) damping (decoherence) rate  $\Gamma$  of 2-state oscillations given by

$$\Gamma \propto (\Delta I)^2 / 4S_0 \quad (\text{so weak-coupling condition equivalent to } \Gamma \ll \omega_0)$$

decoherence not associated with M

(b) both in QM and in MR, (but for different reasons!) output of **detector**,  $q(t) \equiv (I(t) - I_0) / (\Delta I/2)$ , has correlations

$$K_M(t_i, t_j) \equiv \langle q(t_i) q(t_j) \rangle \text{ which are } \textbf{identical} \text{ to those of S.}$$

(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.

\*but cf. Williams and Jordan, PRL 100, 026804 (2008)

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.

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

Ruskov et.al. claim:

- a) For QM, both terms nonzero and give (for  $\Gamma \ll \omega_0$ ),  

$$K_M(\tau) = \cos \omega\tau = K(\tau)$$
[at first sight surprising!]

- b) In MR theory,

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

(“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”)

**This goes far beyond the concept of NIM as introduced by LG!**

**Conclusion: It is certainly possible that (\*) may be tested by a scheme involving weak measurements. But not this way!**