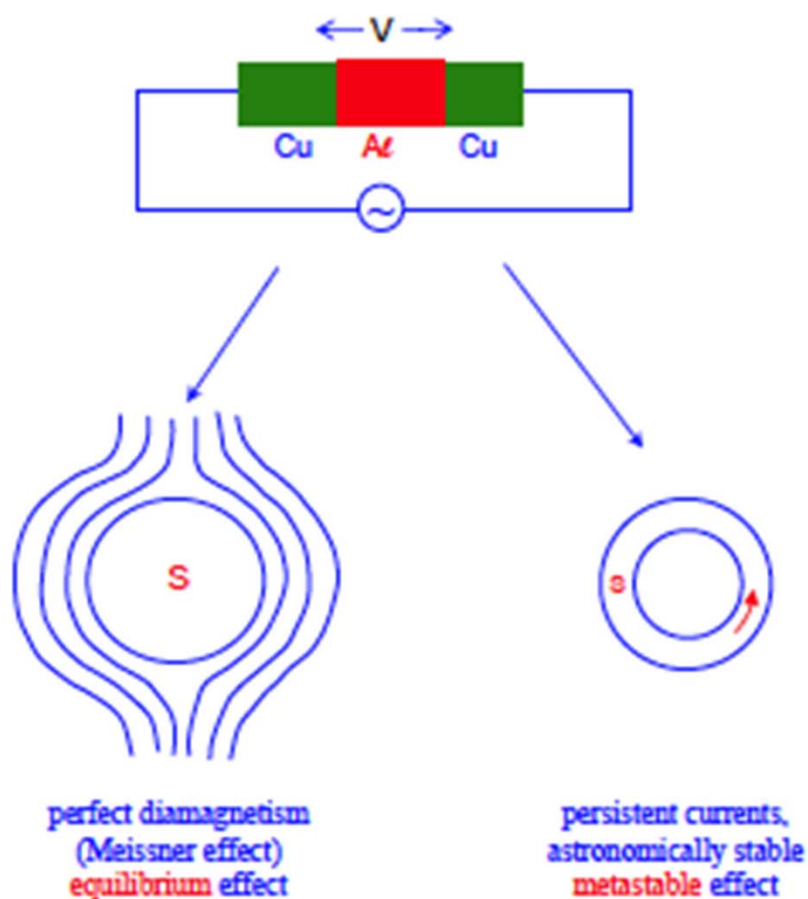
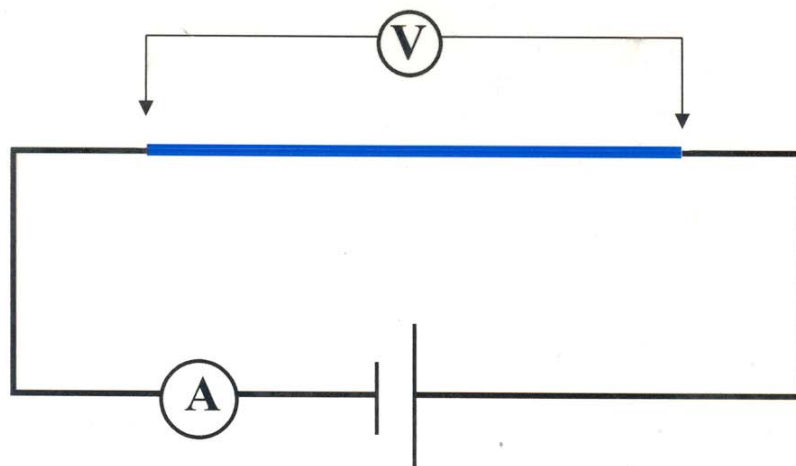


WHAT IS SUPERCONDUCTIVITY?

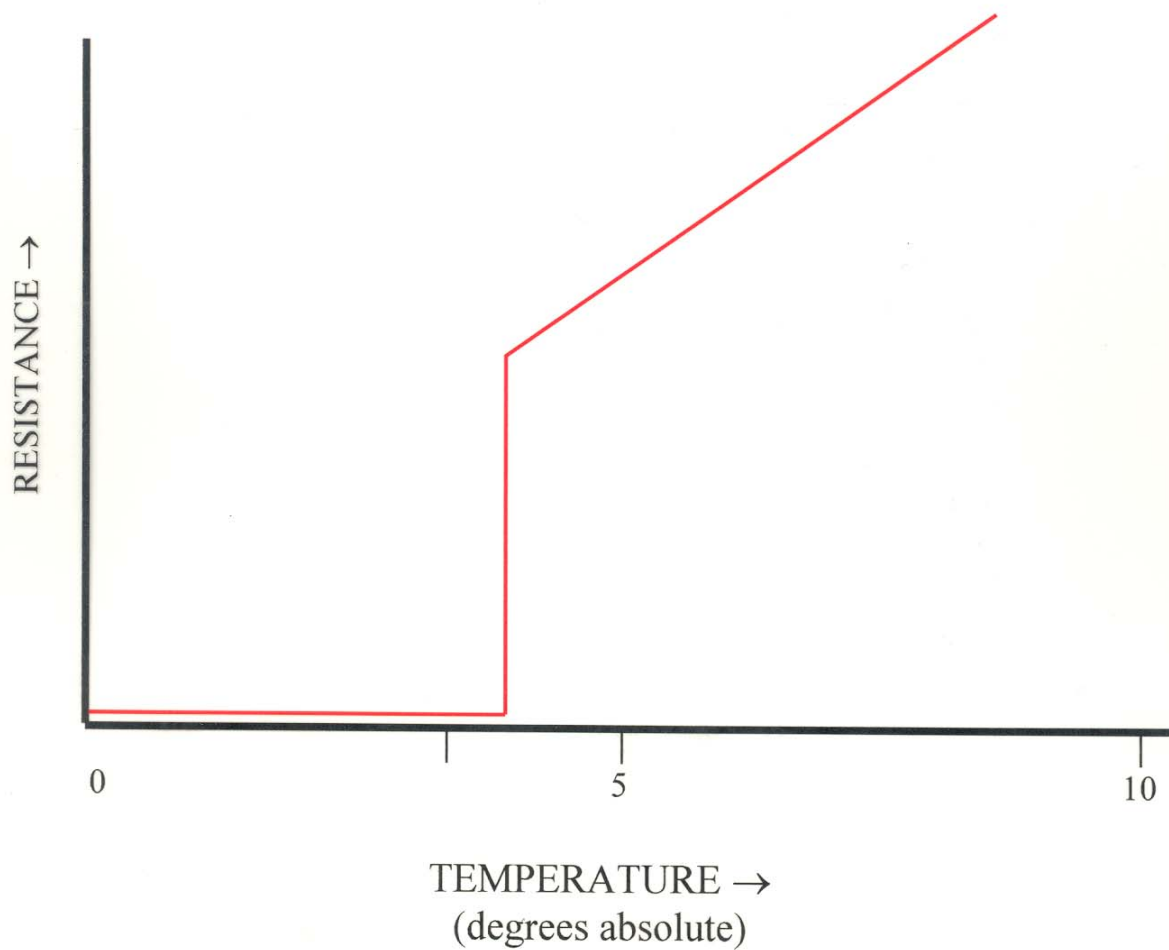
Basic expt: (Onnes 1911)



No a priori guarantee these two phenomena always go together!
(but in fact seem to, in all "superconductors" known to date).

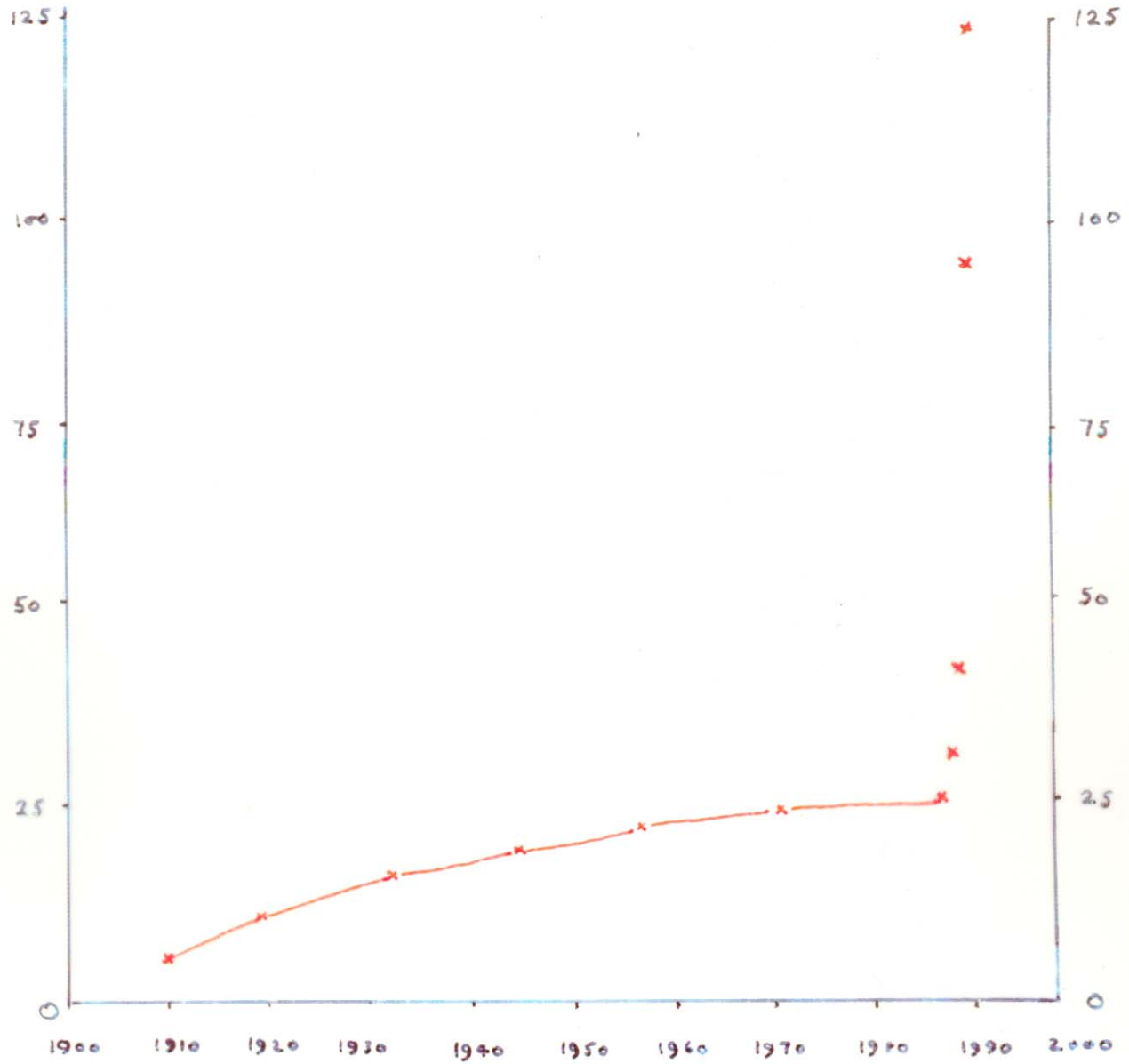


resistance of **—** = V/A = voltage/current



HISTORY OF THE HIGHEST TEMPERATURE

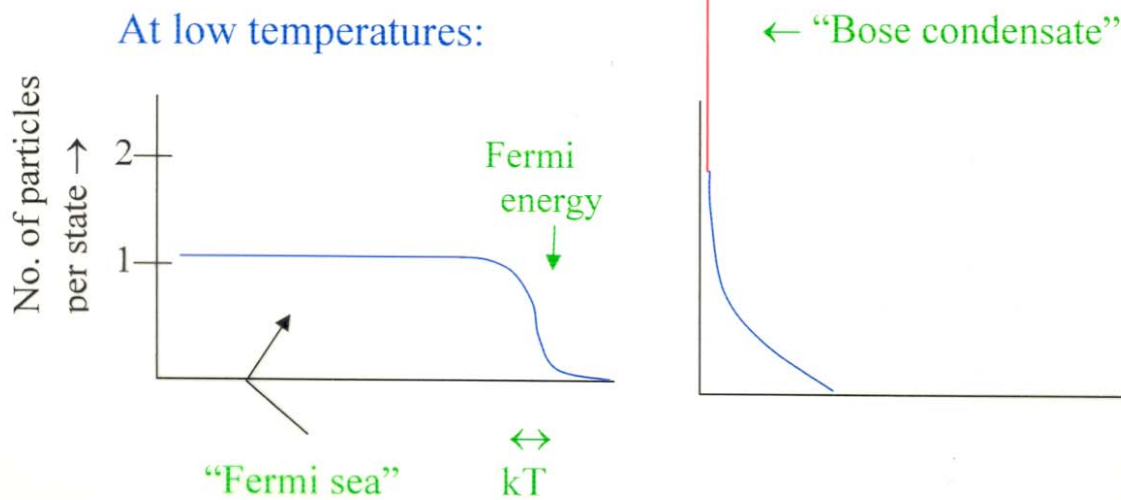
("T_c") AT WHICH SUPERCONDUCTIVITY KNOWN



PHYSICS OF SUPERCONDUCTIVITY

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

0, 1, 2, ... bosons
 $\frac{1}{2}, \frac{3}{2}, \frac{5}{2}, \dots$ fermions



Electrons in metals: spin $\frac{1}{2} \Rightarrow$ fermions

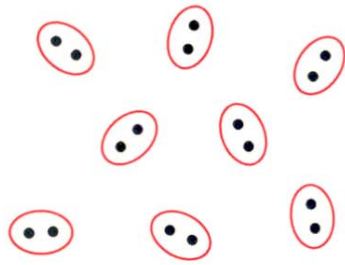
But a compound object consisting of an **even** no.

of fermions has spin 0, 1, 2 ... \Rightarrow boson.

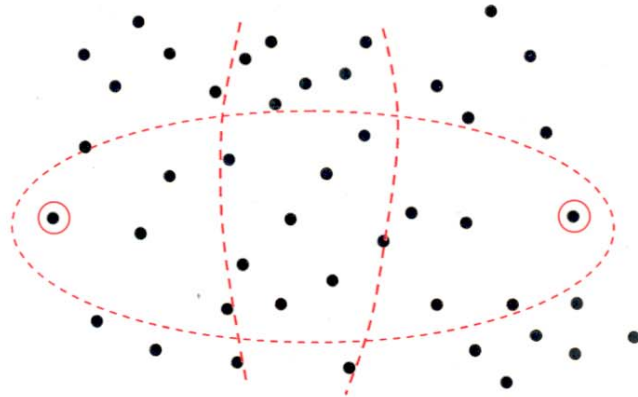
(Ex: $2p + 2n + 2e = {}^4\text{He}$ atom)

\Rightarrow can undergo Bose condensation

Pairing of electrons:



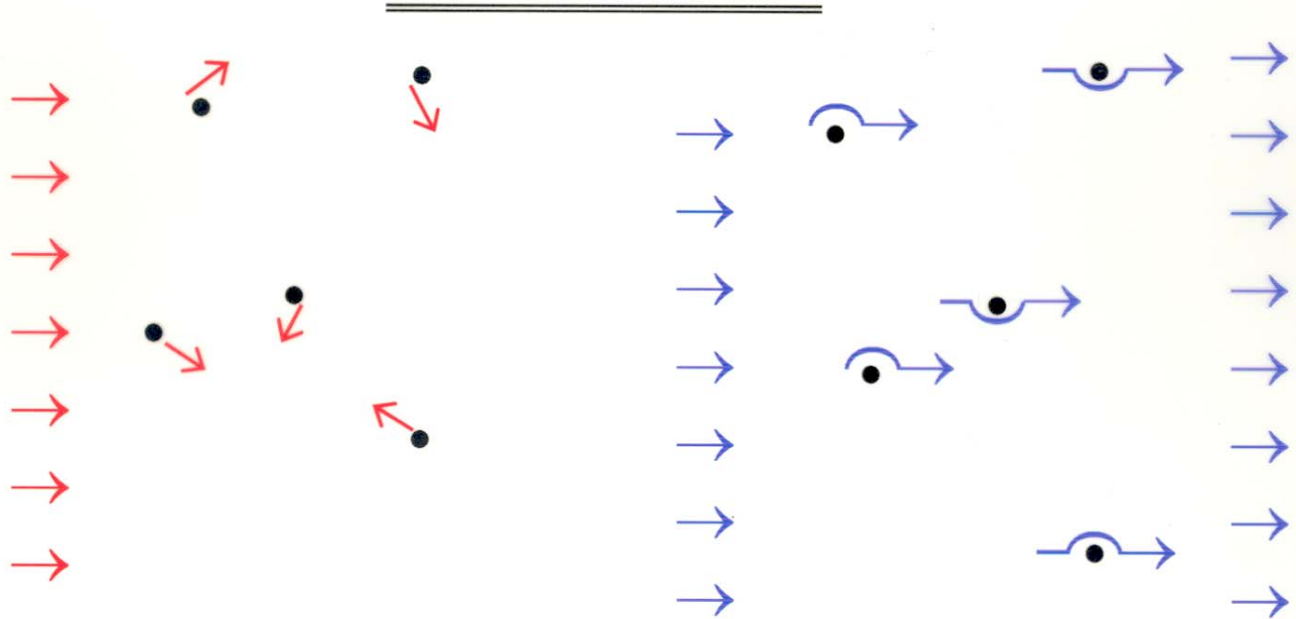
“di-electronic molecules”



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)



Single electrons in normal metal

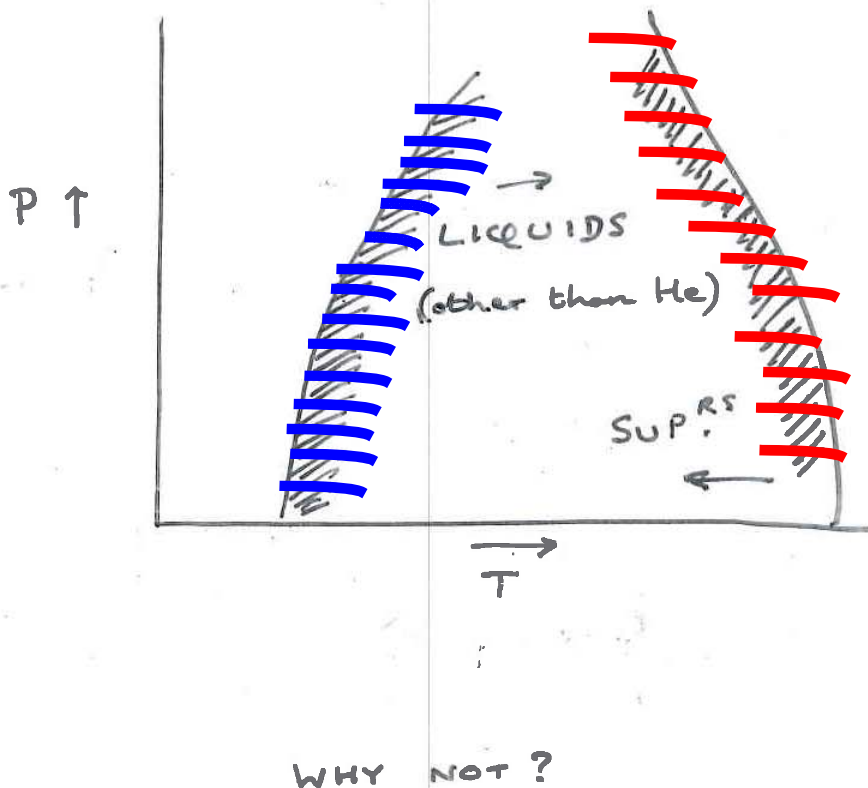
Cooper pairs in superconductor

Some questions about the future of superconductivity

1-Will we ever get a theory of high temperature superconductivity comparable to BCS theory of conventional superconductors?

2-Will we be able to build a robust room-temperature superconductor? What will be the consequences?

3-Will we ever find a (terrestrial) superconducting liquid ? (cf. neutron stars)



SOME OBVIOUSLY TRUE FACTS ABOUT THE
PHYSICAL WORLD:

1. The Sun goes around the Earth.

Copernicus 1543

2. Objects on which no forces act come to rest.

Galileo 1610

3. The time at which an event occurs cannot depend on the state of motion of the observer.

Einstein 1905

4. Physical objects behave in the same way whether or not observed.

Heisenberg 1926

5. The Universe is eternal and unchanging.

Hubble 1933

6. Isolated physical systems possess properties in their own right.

Bell 1964

SOME MORE OBVIOUS TRUE FACTS ABOUT THE PHYSICAL WORLD

LAB 3

1-Statements about what “would have happened” are either true or false

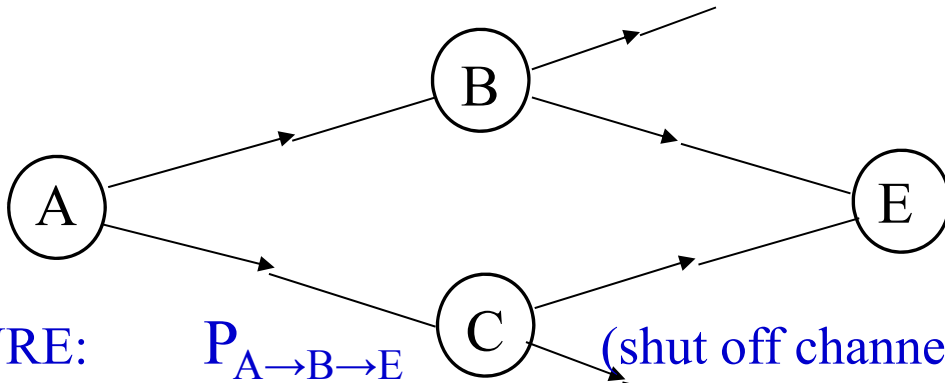
2-The past can influence the present, and the present the future, not viceversa

3- All accounts of “paranormal” phenomena are the results of fraud/hallucination/...

4-The properties of big things are consequences of the properties of the little things, of which they are composed

5-There is no “purpose” in the Universe.

INTERFERENCE OF AMPLITUDES



MEASURE:

$$P_{A \rightarrow B \rightarrow E}$$

$$P_{A \rightarrow C \rightarrow E}$$

(shut off channel C)

(shut off channel B)

(both channels open)

EXPTL. FACT: $P_{A \rightarrow E}^{\text{tot}}$

$$P_{A \rightarrow E}^{\text{tot}} \neq P_{A \rightarrow B \rightarrow E} + P_{A \rightarrow C \rightarrow E}$$

QM ACCOUNT:

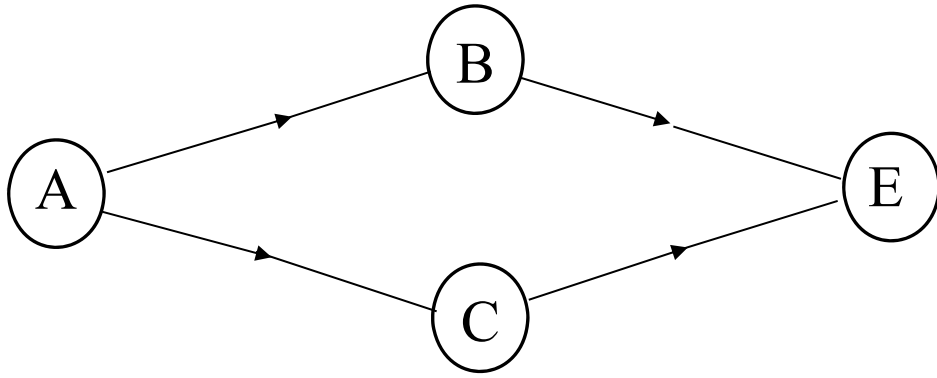
$$P_{A \rightarrow E}^{\text{tot}} = \left| \sum_{\text{paths}} A_{A \rightarrow E}^{(\text{path})} \right|^2$$

vanishes unless both A's nonzero

↓

$$= P_{A \rightarrow B \rightarrow E} + P_{A \rightarrow C \rightarrow E} + 2\text{Re}(A_{A \rightarrow B \rightarrow E} \circlearrowleft A_{A \rightarrow C \rightarrow E}^*)$$

⇒ amplitude must be nonzero for each of two paths,
not just for ensemble but for each member of it
And yet....



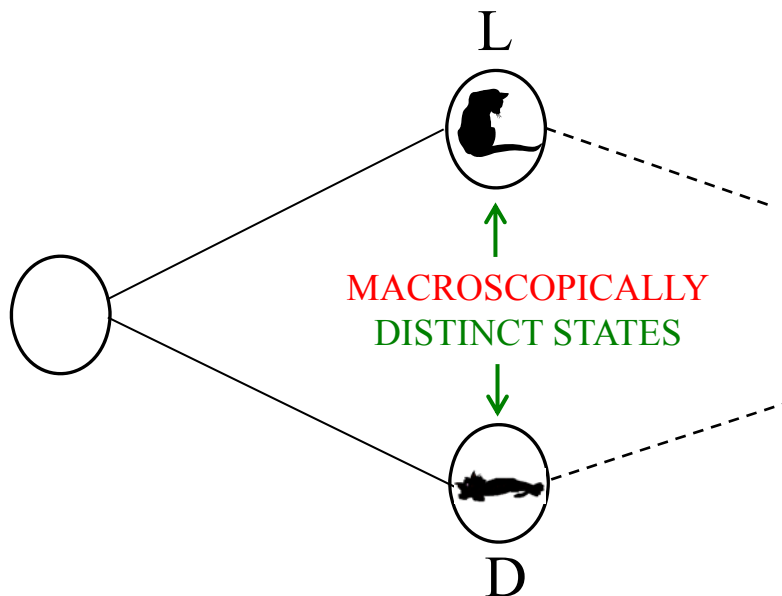
At microlevel:

Directly observed phenomenon of interference

⇒ simultaneous “existence” of amplitudes for two alternative paths for each individual member of ensemble

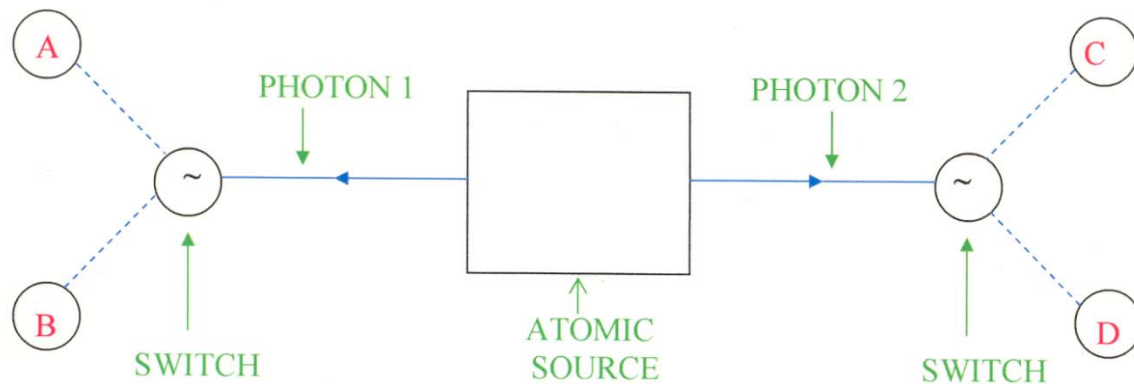
⇒ neither outcome “definitely realized”

Now, extrapolate formalism to macrolevel (Schrödinger):



Is each cat of ensemble **either** in state L **or** in state D?

EXPERIMENTS ON CORRELATED PHOTONS



$(A) \equiv \begin{array}{|c|} \hline \square \\ \hline \end{array} \begin{array}{|c|} \hline \square \\ \hline \end{array}, \text{ etc.}$
↖ transm. axis = \tilde{a}

DEFINITION: If photon 1 is switched into counter “A”

If counter “A” clicks, $A = +1$ (DF.)

If counter “A” does not click, $A = -1$ (DF.)

NOTE:

If photon 1 switched into counter “B”, then A is **NOT DEFINED.**

Experiment can measure

$\langle AC \rangle_{\text{exp}}$ on one set of pairs ($1 \rightarrow \text{“A”}, 2 \rightarrow \text{“C”}$)

$\langle AD \rangle_{\text{exp}}$ on another set of pairs ($1 \rightarrow \text{“A”}, 2 \rightarrow \text{“D”}$)

etc.

Of special interest is

$$K_{\text{exp}} \equiv \langle AC \rangle_{\text{exp}} + \langle AD \rangle_{\text{exp}} + \langle BC \rangle_{\text{exp}} - \langle BD \rangle_{\text{exp}}$$

for which Q.M. makes clear predictions.

POSTULATES OF “OBJECTIVE LOCAL” THEORY:

- (1) Local causality
- (2) Induction
- (3) Microscopic realism OR macroscopic

“counter-factual definiteness”

BELL’S THEOREM

1. (3) → For each photon 1, EITHER $A = +1$ OR $A = -1$, **independently** of whether or not A is actually measured.
2. (1) → Value of A for any particular photon 1 unaffected by whether C or D measured on corresponding photon 2. : etc.
3. ∴ For each pair, quantities **AC, AD, BC, BD** exist, with A, B, C, D, = ± 1 and **A the same** in (AC, AD) (etc.)
4. Simple algebra then → for each pair, $AC + AD + BC - BD \leq 2$

5. Hence for a **single ensemble**,

$$\langle AC \rangle_{\text{ens}} + \langle AD \rangle_{\text{ens}} + \langle BC \rangle_{\text{ens}} - \langle BD \rangle_{\text{ens}} \leq 2$$

6. (2) → $\langle AC \rangle_{\text{exp}} = \langle AC \rangle_{\text{ens}}$, hence the measurable quantity

$$K_{\text{exp}} \equiv \langle AC \rangle_{\text{exp}} + \langle BC \rangle_{\text{exp}} + \langle BC \rangle_{\text{exp}} - \langle BD \rangle_{\text{exp}}$$

satisfies

$K_{\text{exp}} \leq 2$, Obj. Local Theory

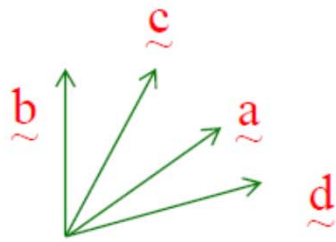
OBJECTIVE LOCAL THEORY: $K_{\text{exp}} \leq 2$.

QM: If polarizer settings are \underline{a} , \underline{b} , \underline{c} , \underline{d}

then e.g. for a 0^+ transition predict

$$\langle AC \rangle = \cos(2\theta_{\underline{a} \cdot \underline{c}}), \text{ etc.}$$

\Rightarrow for



QM predicts (ideal case)

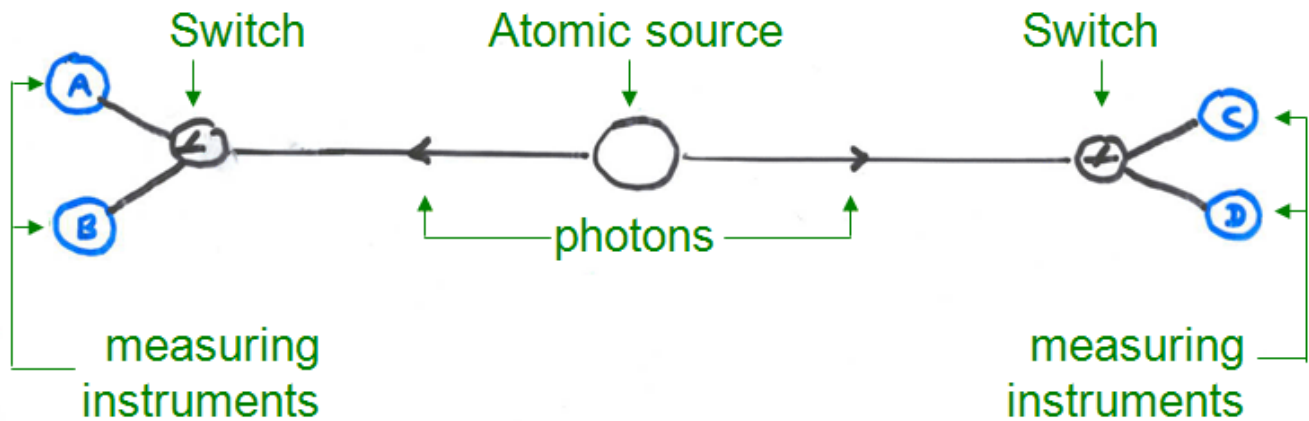
$$\underline{K_{\text{exp}}} = 2\sqrt{2}$$

\Rightarrow Exptl. Predictions of QM incompatible with those of any theory embodying

- Local causality
- Induction
- Macroscopic counter-factual definiteness

1. “It is a fact that either A would have clicked or A would have clicked”
2. “Either it is a fact that A would have clicked, or it is : that A would not have clicked”

COULD THE “ARROW OF TIME” REVERSE LOCALLY (AND TEMPORARILY)?



Experimental fact:

The observed correlations are (consistent with QM, but) inconsistent with any theory embodying

- objectivity
- locality
- induction** — i.e., “past causes future, not vice versa”

Could the outcome of the measurements propagate “backwards in time” and affect the initial state?

Formally OK: can it be reconciled with the (macroscopic) 2nd law (increase of entropy)?

IMPLICATIONS FOR “FREE WILL”??