Does the Everyday World Really Obey Quantum Mechanics?

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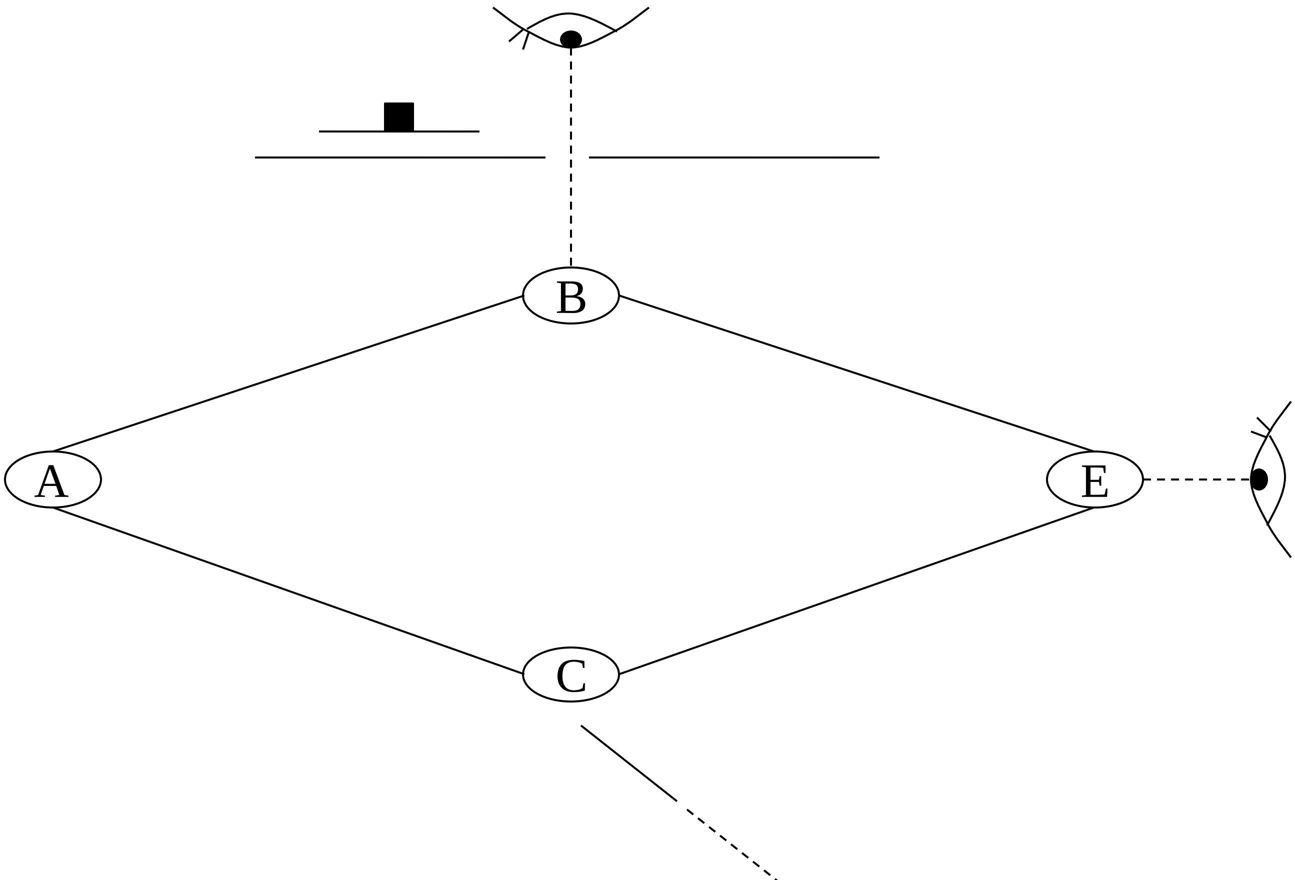
Basic "experimental fact"



Experiment:

1. Shut off C, measure Prob. (A→B→E) $(\equiv "P_B")$

2. Shut off B, measure Prob. (A→C→E) $(\equiv "P_C")$

3. Open both paths, measure Prob. $\left(A \rightarrow \begin{Bmatrix} B \\ C \end{Bmatrix} \rightarrow E\right)$ $(\equiv P_{BorC}")$

<u>Result</u>:

A. Look to see whether path B or C is followed:

a) Every individual atom (etc.) follows <u>either</u> B <u>or</u> C.

b) $P_{B\ or\ C} = P_B + P_C$ ("common sense" result)

B. Don't look:

$P_{B\ or\ C} \neq P_B + P_C$

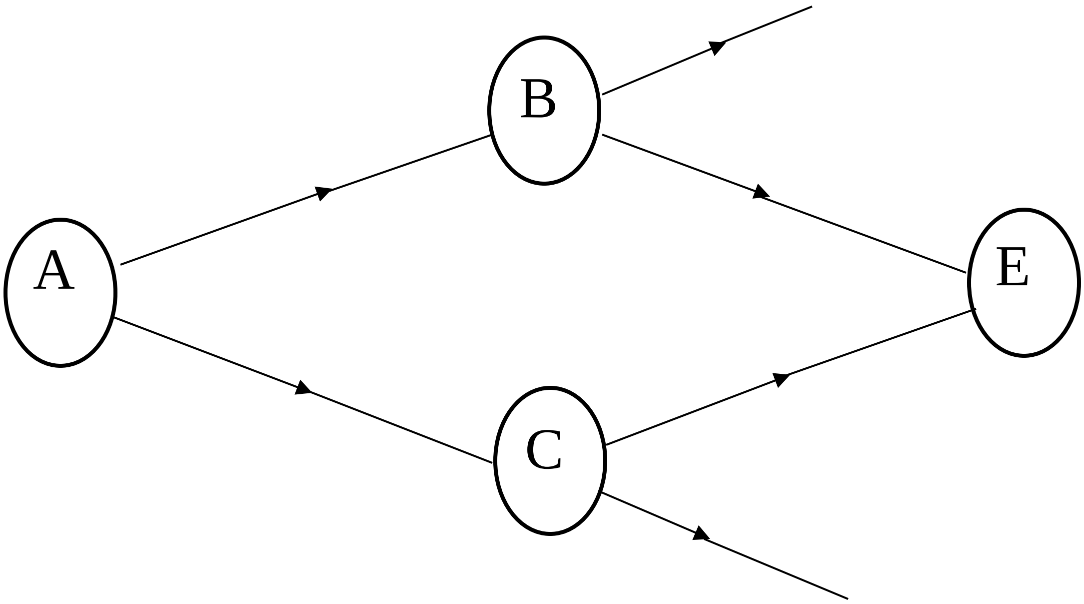
In fact, can have:

$P_B \neq 0$, $P_C \neq 0$, but $P_{B\ or\ C} = 0$!

NEITHER B NOR C "SELECTED" … BY

EACH INDIVIDUAL ATOM!

Account given by quantum mechanics:



Each possible process is represented by a probability amplitude A which can be positive or negative

- Total amplitude to go from A to E sum of amplitudes for possible paths, i.e. $A \rightarrow B \rightarrow E$ and/or $A \rightarrow C \rightarrow E$

- Probability to go from A to E = square of total amplitude

1. If C shut off: $A_{tot} = A_B \Rightarrow P \equiv P_B = A_B^2$

2. If B shut off: $A_{tot} = A_C \Rightarrow P \equiv P_C = A_C^2$

3. If both paths open:

$A_{tot} = A_B + A_C \leftarrow$ "SUPERPOSITION"

$\Rightarrow P \equiv P_{B\text{ or }C} = A_{tot}^2 = (A_B + A_C)^2 = A_B^2 + A_C^2 + 2\,A_B\,A_C$

$\Rightarrow P_{B\text{ or }C} = P_B + P_C + 2A_BA_C$

↑ "interference" term

TO GET INTERFERENCE, A_B AND A_C MUST SIMULTANEOUSLY "EXIST" FOR EACH ATOM

$$P_{B\text{ or }C} = P_B + P_C + 2A_BA_C$$

Suppose $A_C = \pm A_B$, at random. Then

<u>average</u> of $P_{B\text{ or }C}$ is

av. of $A_B\ A_C$

$$\overline{P}_{B\text{ or }C} = P_B + P_C + 2\overline{A_BA_C}$$

but $\overline{A_BA_C}$ = av. of $+A_B^2$ and $-A_B^2$ = 0

so

$\overline{P}_{B\text{ or }C} = P_B + P_C$ ← "COMMON SENSE" RESULT,

i.e."as if" each system chose path B or path C

WHEN A_B AND A_C SIMULTANEOUSLY "EXIST", NEITHER B NOR C "SELECTED".

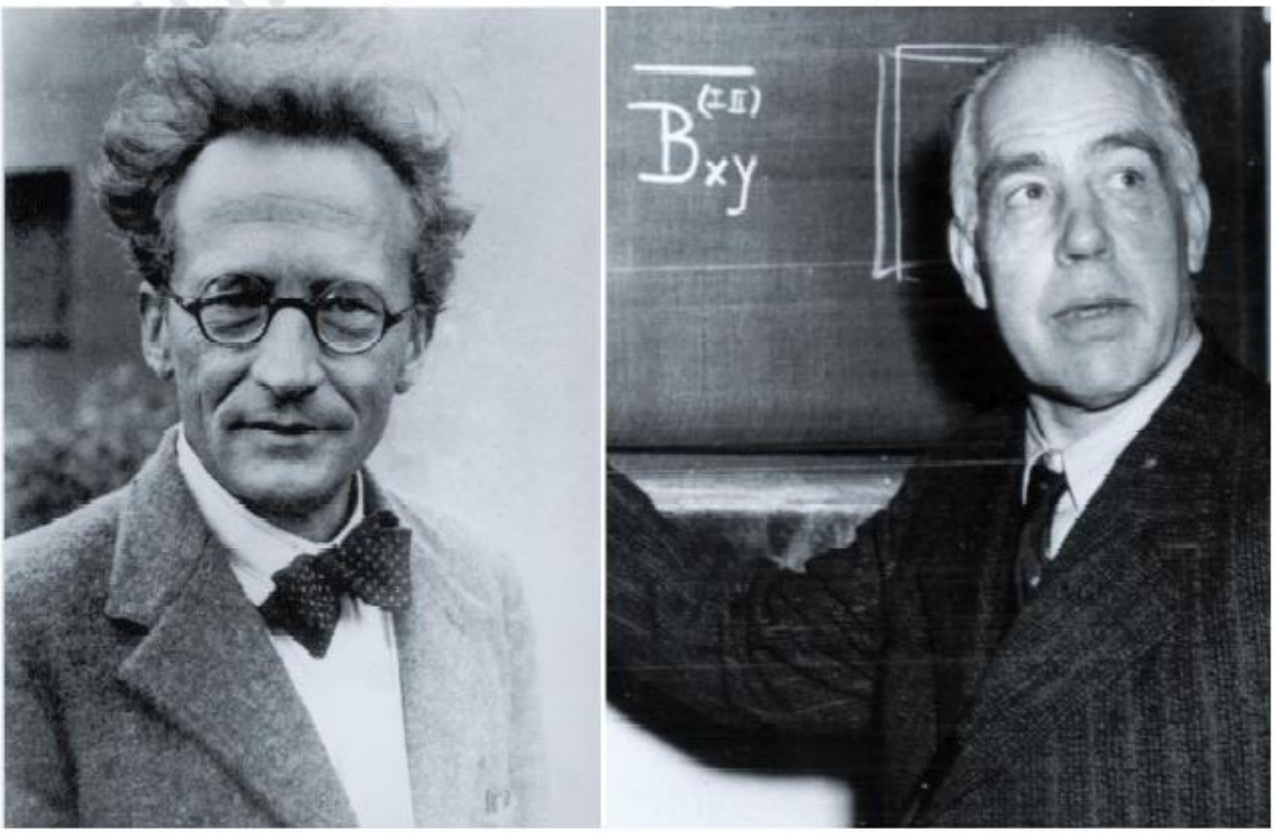
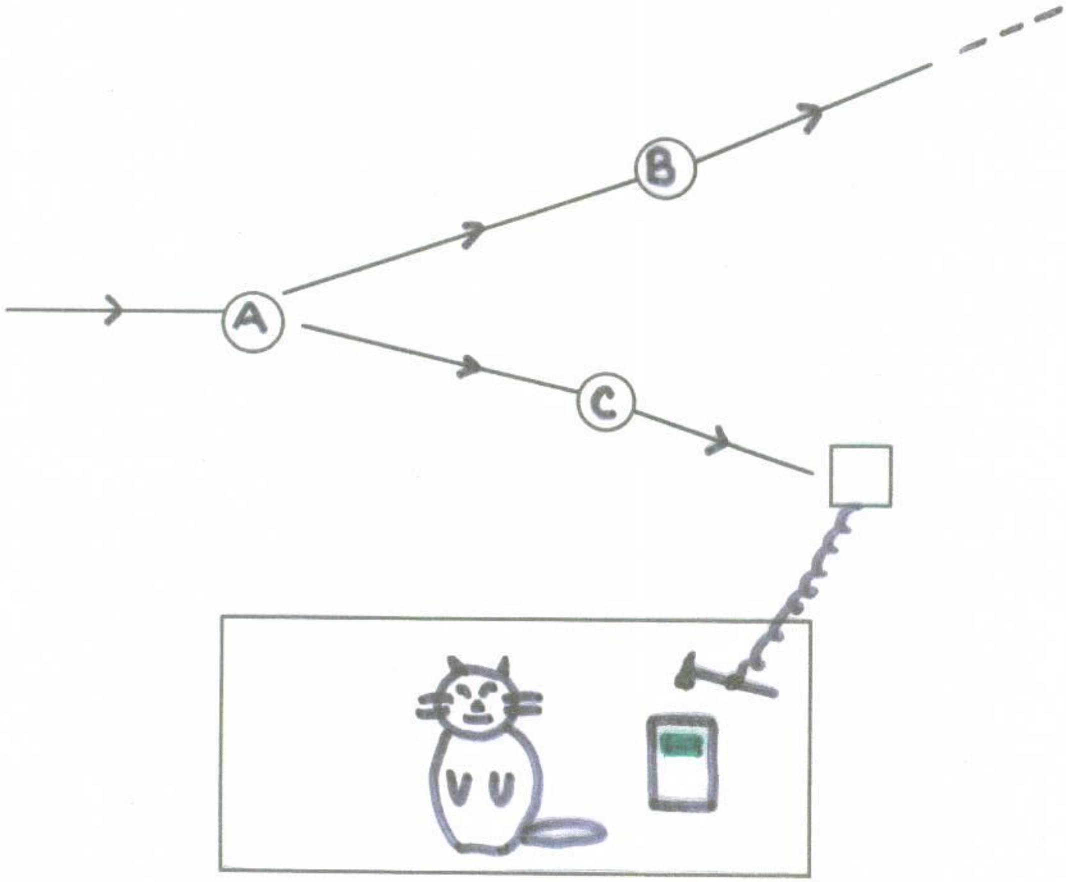


Figure 1 **Erwin Schrödinger (left) and Niels Bohr. Bohr claimed that a momentum kick, imparted by any measurement of particle position, could explain the disappearance of quantum interference in ‘two-slit’ experiments. A new experiment[1] shows that this effect is too small, and the disappearance must instead be explained using Schrödinger’s ‘entanglement’ between quantum states.**



In quantum mechanics, if state 1 $\rightarrow$ state 1' and state 2 $\rightarrow$ 2' , then superposition of 1and 2 $\rightarrow$ superposition of 1' and 2'.

Here, B $\rightarrow$ cat alive
C $\rightarrow$ cat dead

$\therefore$ Superposition of B and C
$\rightarrow$ superposition of "alive and "dead"!

i.e.

$$\begin{cases} \text{ampl. (cat alive)} \neq 0 \\ \text{ampl. (cat dead)} \neq 0 \end{cases}$$

Some "resolutions" of the Cat paradox

a) Assume quantum mechanics is universal

i. "Orthodox" resolution

Recall:

$P_{B\text{ or }C} = P_B + P_C + 2A_BA_C \leftarrow$ "interference" term

If $A_C = \pm A_B$ at random

averages to zero

$P_{B\text{ or }C} = P_B + P_C + 2\overline{A_BA_C} = P_B + P_C$

Effect of "outside world" is, generally speaking, to randomize sign; more effective as system gets larger.

$\Rightarrow$ interference term vanishes for "everyday" objects (cats!) ("decoherence")

$\Rightarrow$ each system chooses either B or C?

ii. extreme statistical

iii. "many-worlds"

More "resolutions"

b) Assume quantum mechanics breaks down at some point en route from the atom to the cat

e.g. GRWP* theory

- universal, non-quantum mechanical "noise" background

- induces continuous, stochastic evolution to one or the other of 2 states of superposition

- trigger: "large" ($\gtrsim 10^{-5}$cm) separation of center of mass of N particles in 2 states

- rate of evolution ⍰ N

- in typical "measurement" situations, all statistical predictions identical to those of standard quantum mechanics

also, theories based (e.g.) on special effects of gravity (Penrose, ...)

"macrorealism"

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*Ghirardi, Rimini, Weber , Pearle

Is quantum mechanics the whole truth?
How do we tell?
If all "everyday-scale" bodies have the property that the interference term is randomized ("decoherence"), always get "common sense" result, i.e. all experimental results will be "as if" one path or the other were followed.

$\Rightarrow$ cannot tell.
So: must find "everyday-scale" object where decoherence is not effective. Does any such exist?

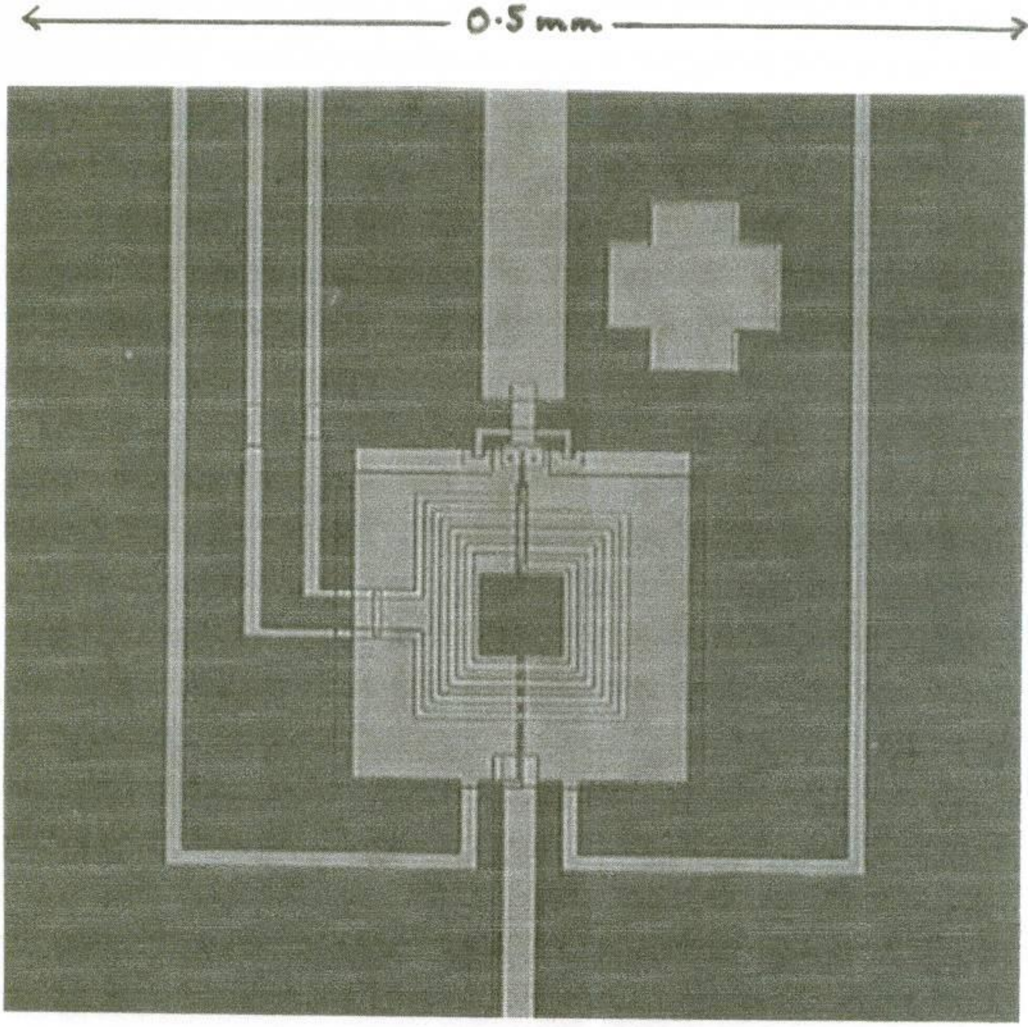
Essential:
- difference of two states is at "everyday" level
- nevertheless, relevant energies at "atomic" level
- extreme degree of isolation from outside world
- very low intrinsic dissipation

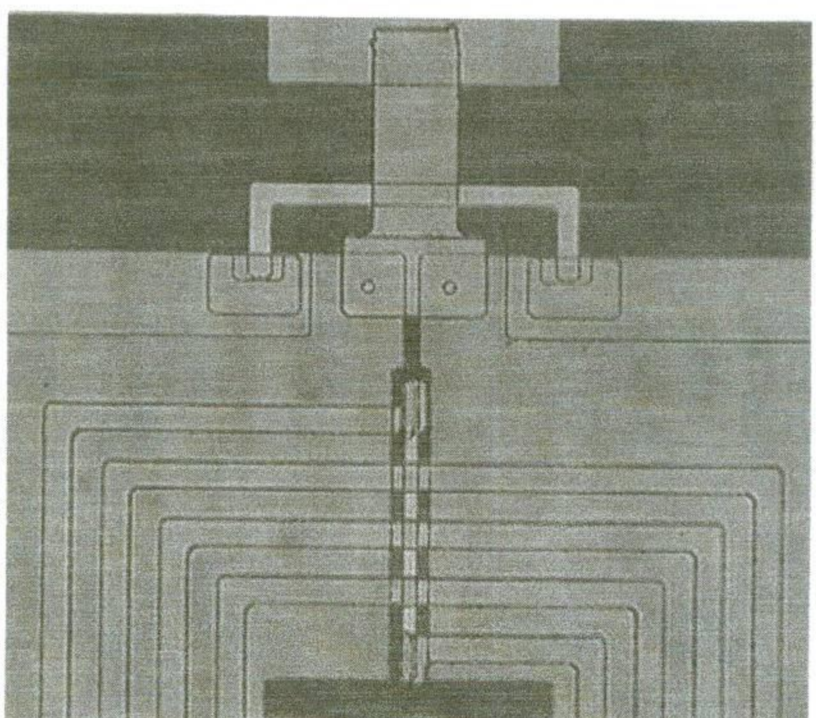
QM CALCULATIONS HARD!

BASE ON:

a) A PRIORI "MICROSCOPIC" DESCRIPTION ✗

b) EXPTL. BEHAVIOR IN "CLASSICAL" LIMIT ✓


0.5 mm



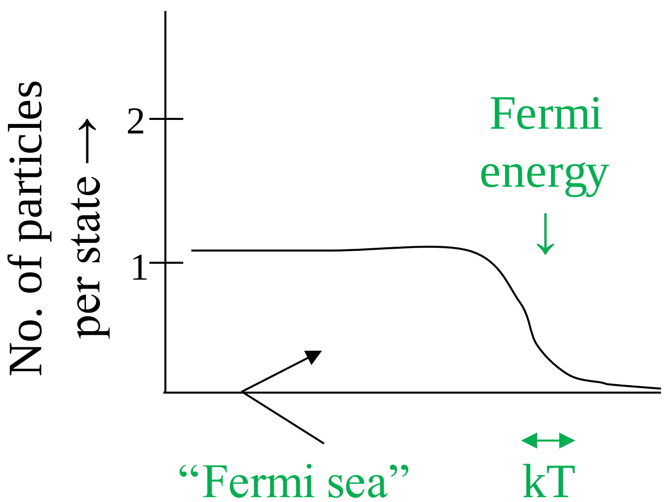
PHYSICS OF SUPERCONDUCTIVITY

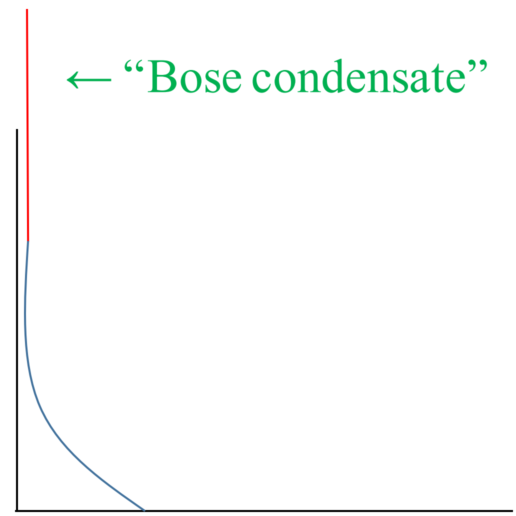
"Spin" of elementary particles $= \frac{n}{2}\hbar$

$0, 1, 2 \ldots$ bosons

$\frac{1}{2}, \frac{3}{2}, \frac{5}{2} \cdots$ fermions

At low temperatures:





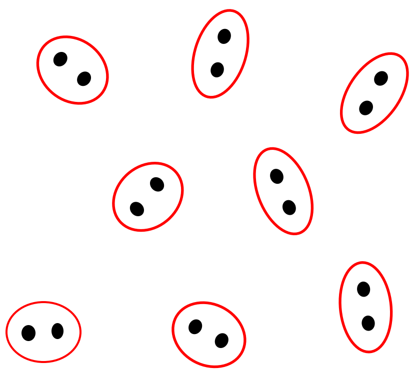
Electrons in metals: spin ½ ⇒ fermions

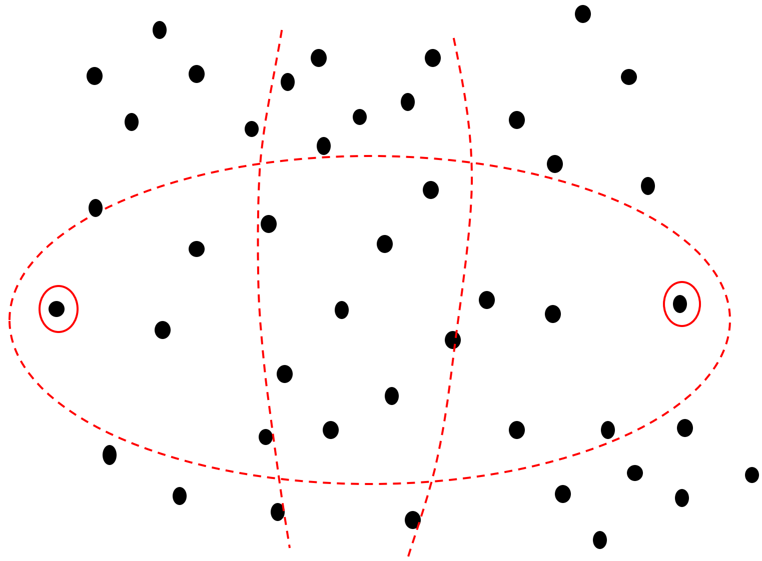
But a compound object consisting of an even no. of fermions has spin $0, 1, 2 \ldots \Rightarrow$ boson.

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

⇒ can undergo Bose condensation

Pairing of electrons:



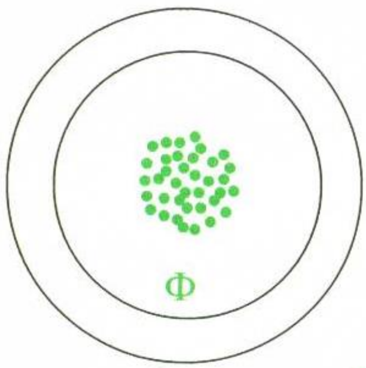


"di-electronic molecules"   Cooper Pairs

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):

integer

$$K \equiv \oint \mathbf{v} \cdot \mathbf{dl} = \frac{h}{2m}\,(n - \Phi/\Phi_o)$$

"flux quantum" $h/2e$

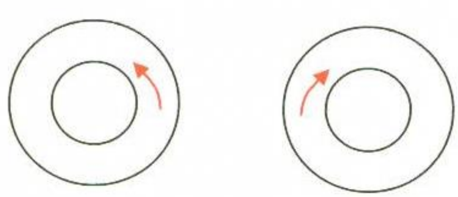
$E \propto K^2$

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

$\Rightarrow$ all pairs at rest.

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

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



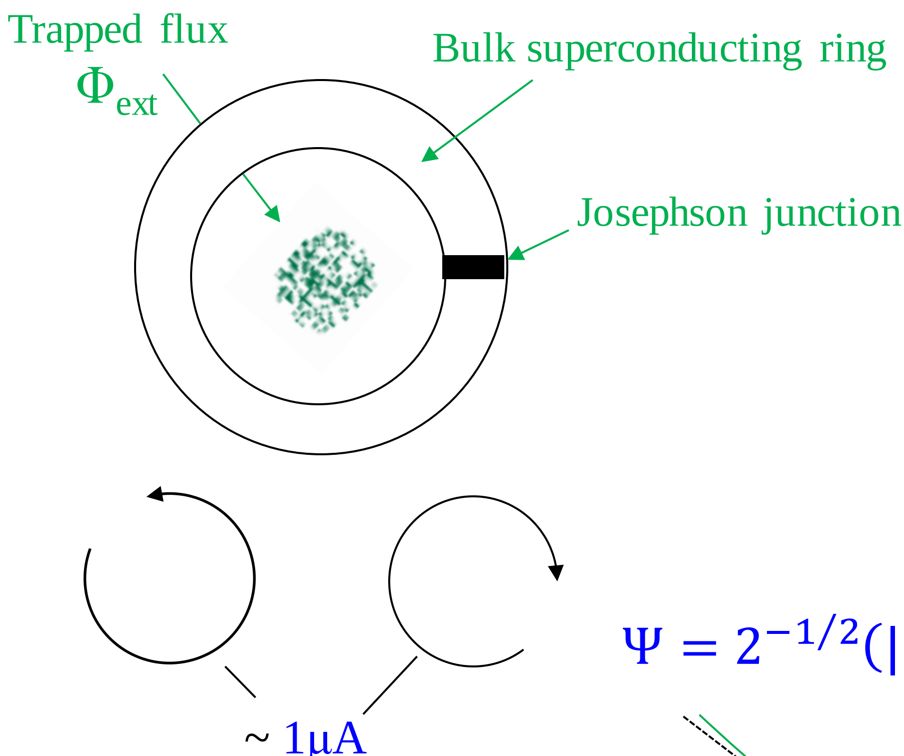
Either all pairs rotate clockwise

Or all pairs rotate anticlockwise

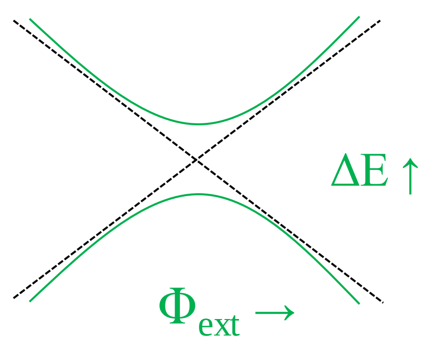
Note: state with 50% ↖ and 50% ↗

strongly forbidden by energy considerations

Josephson circuits



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



Evidence:

a) spectroscopic:
(SUNY, Delft 2000)

b) real-time oscillations (like NH_3)

between ↺ and ↻

(Saclay 2002, Delft 2003) (Q_φ ~ 50-100)

Other systems where Quantum Mechanics has been tested in direction of "Everyday World":

SYSTEM	NO. OF PARTICLES INVOLVED IN SUPERPOSITION
Free-space molecular diffraction (C_{60},C_{70})	~ 1200
Magnetic Biomolecules	~ 5000
Quantum-Optical Systems	~ 10^6
[SQUIDS	~ 10^{10}]

Where to go next?

- Larger/more complex objects
- Superpositions of states of different biological functionality (Rhodopsin/DNA/....)
- * Direct Tests of Macrorealism

Tests of macrorealism versus quantum mechanics using SQUID

For a SQUID, define the class of macrorealistic theories by the postulates

(i) System always in either state + or state – , whether or not observed.

(ii) Can in principle determine whether + or – without effect on subsequent behavior ("noninvasive measurability").

(iii) Induction

There is a certain quantity K, whose value can be directly inferred from an appropriate series of measurements. Predictions for K:

(a)	Any macrorealistic theory:	$K \leq 2$	✓
(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 of SQUID experiment.

a) Experiment doesn't work (i.e., too much "noise" $\Rightarrow$ quantum-mechanical prediction for K is < 2).

b) $K > 2 \Rightarrow$ macrorealism refuted

c) $K < 2 \Rightarrow$ quantum mechanics refuted at everyday level.

This was the situation up to Oct. 2016….

Nov. 2016: experiment done and published!

(G.C. Knee et al. (inc. AJL), Nature Comms. 4 Nov. 2016, DOI:10.1038/ncomms13253).

Result: B (by >80 standard deviations)

i.e.: macrorealism fails at least up to the level of superconducting devices.

Where to go from here?