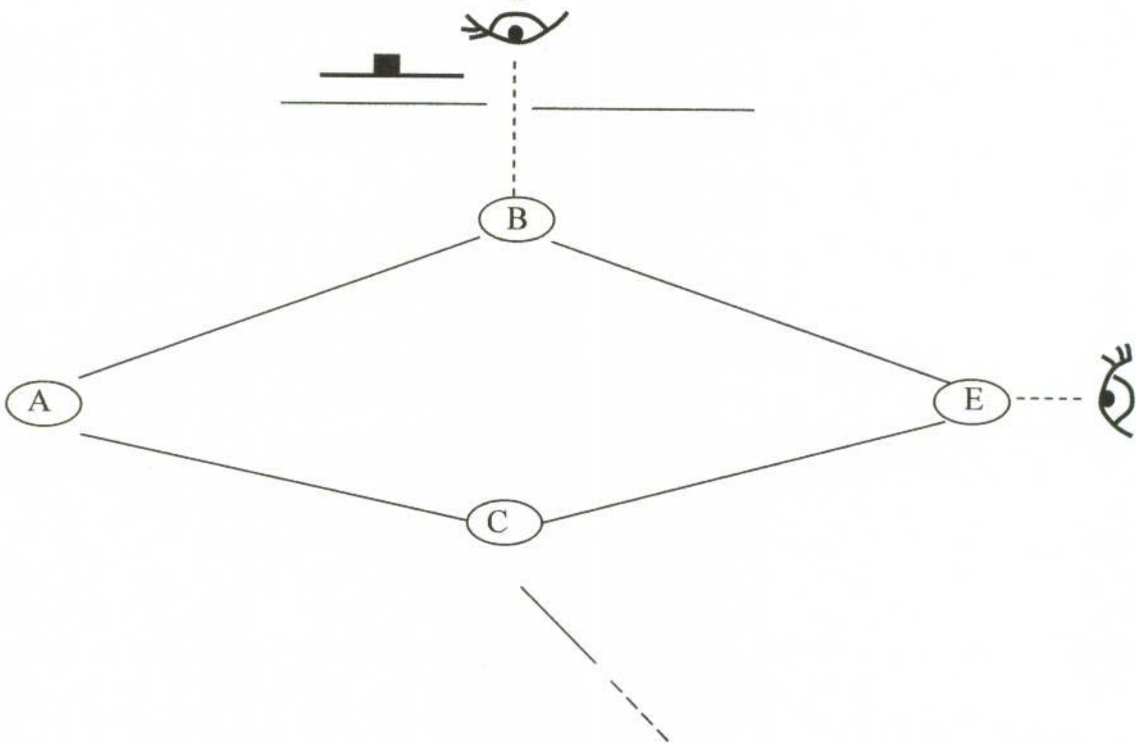
Basic "experimental fact"



Experiment:

1. Shut off C, measure Prob. $(A \rightarrow B \rightarrow E)$ $(\equiv \text{"}P_B\text{"})$

2. Shut off B, measure Prob. $(A \rightarrow C \rightarrow E)$ $(\equiv \text{"}P_C\text{"})$

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

Result:

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

(a) Every individual atom (etc.) follows either B or C.

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

B. Don't look:

$P_{B\text{ or }C} \neq P_B + P_c$

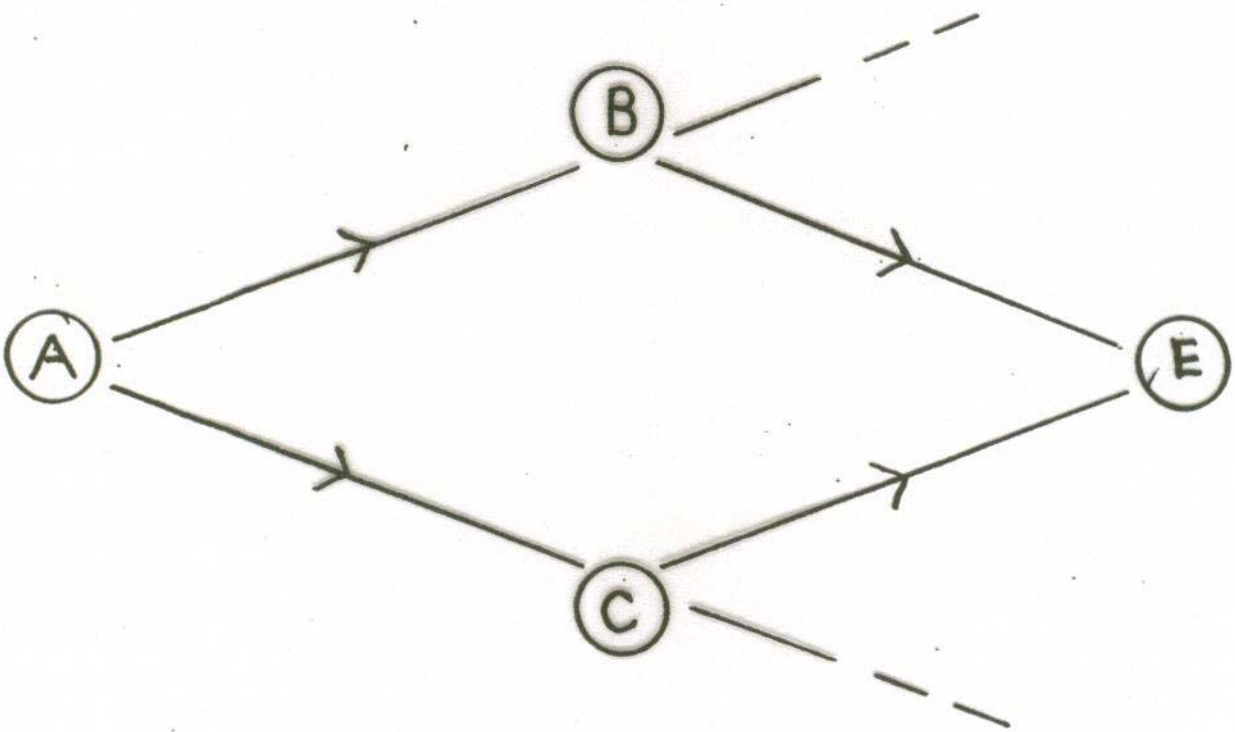
In fact, can have:

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

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→B →E and/or A→C→E

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

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

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

3. If both paths open:

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

$\Rightarrow P = A_{tot}^2 = (A_B + A_C)^2 = A_B^2 + A_C^2 + 2 A_B A_C$

$= P_B + P_C + 2A_BA_C \leftarrow$ "interference" term

$\Leftarrow P_{B \text{ or } C}$

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

Suppose $P_B = P_C$, then $A_B = \pm A_C$.

If $A_B = + A_C$, $P_{B\text{ or }C} = P_B + P_C + 2A_B^2 = 4P_B = 2(P_B + P_C)$

If $A_B = - A_C$, $P_{B\text{ or }C} = P_B + P_C - 2A_B^2 = P_B + P_C - 2P_B = 0$

If $A_B = \pm A_C$, at random

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

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

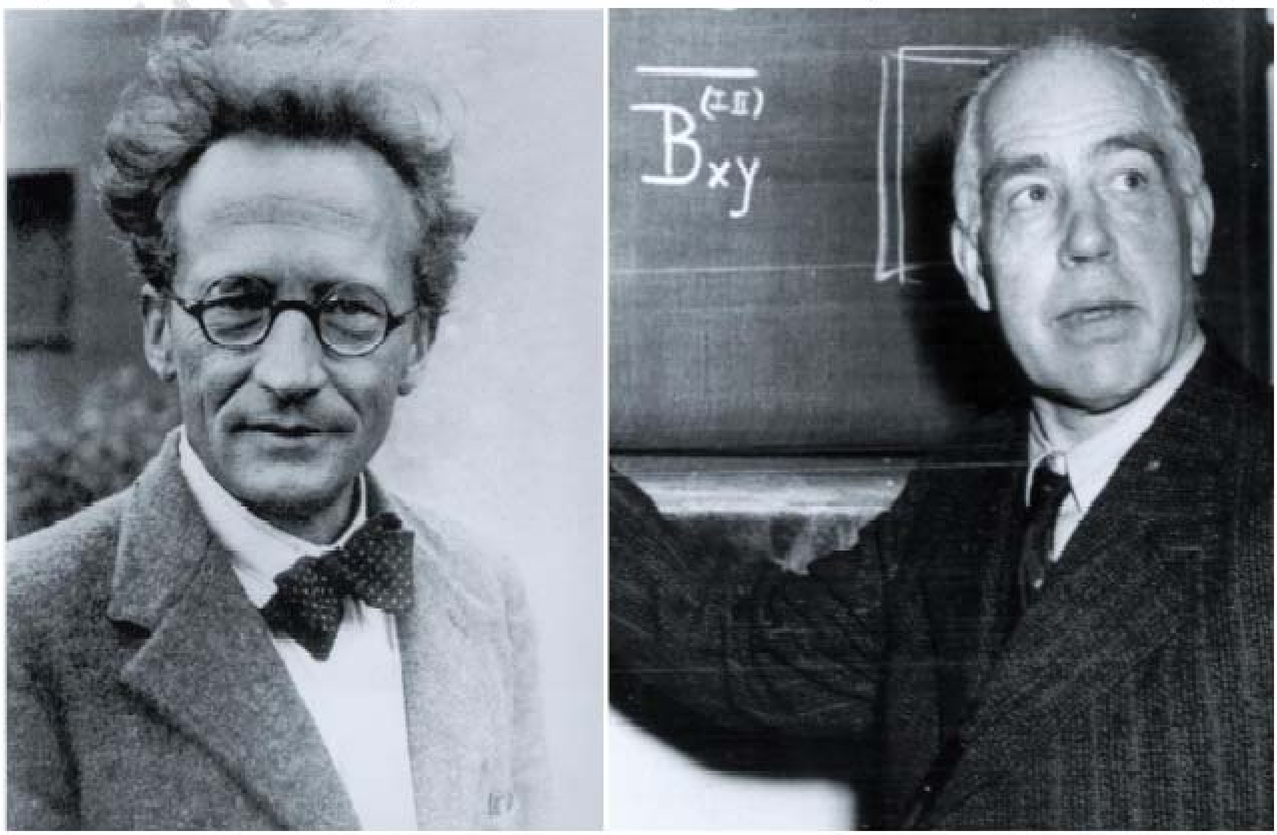
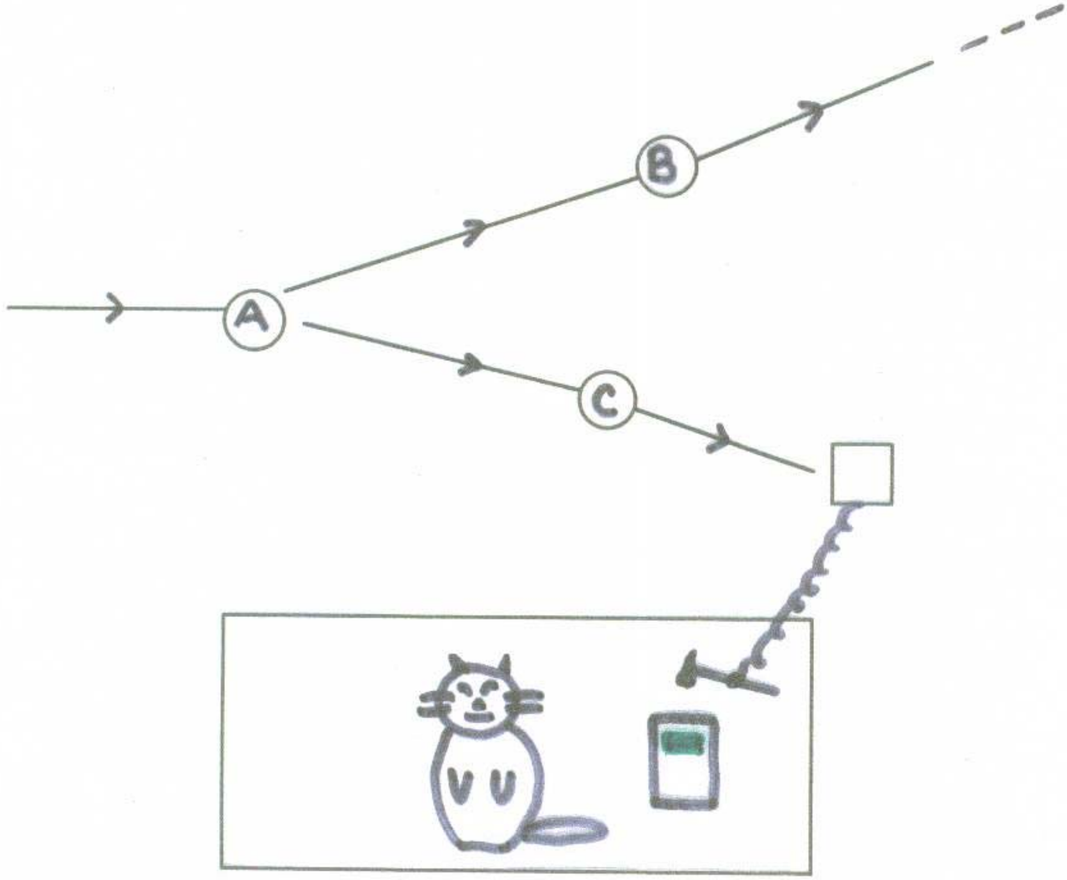


Figure 1 **Erwin Schrödinger (left) and Niels Bohr. Bohr claimed that a momentum kick, imparted by any measurement of particle position, could explain the disappearance of quantum interference in ‘two-slit’ experiments. A new experiment[1] shows that this effect is too small, and the disappearance must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



In quantum mechanics, if state 1 → state 1′ and state 2 → 2′, then superposition of 1 and 2 → superposition of 1′ and 2′.

Here, B → cat alive

C → cat dead

- ∴ superposition of B and C → 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:

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

If $A_C = \pm A_B$ at random,

averages to zero

$$P_{B\,or\,C} = P_B + P_C + 2\overline{A_B A_C} = P_B + P_C$$

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

=> interference term vanishes for "everyday" objects (cats!) ("decoherence")

=> 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 $\propto$ 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

<u>Is</u> quantum mechanics the whole truth?

How do we tell?

If <u>all</u> "everyday-scale" bodies have the property that the interference term is randomized ("decoherence"), then 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:

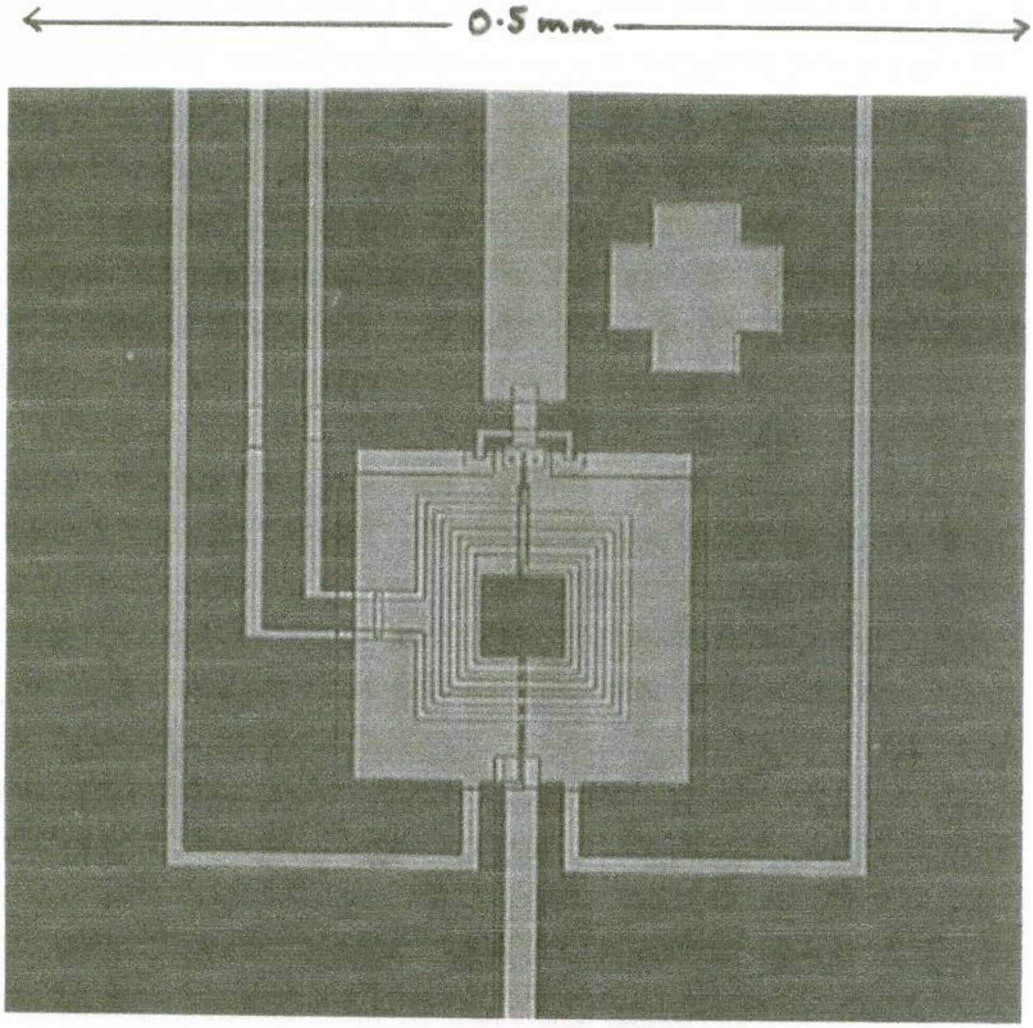
- difference of two states is at "everyday" level
- nevertheless, relevant <u>energies</u> at "atomic" level
- extreme degree of isolation from outside world
- very low intrinsic dissipation

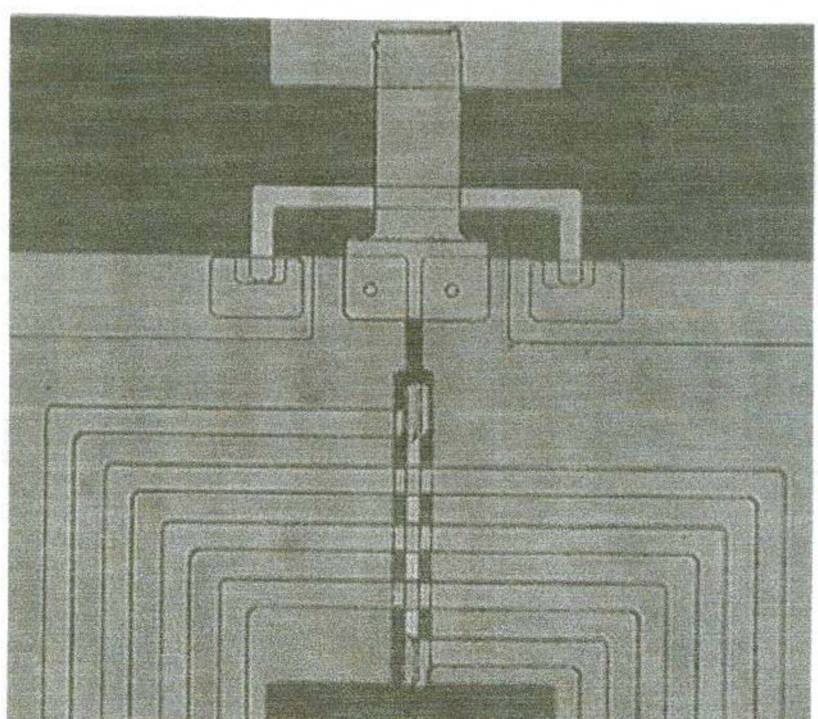
QM CALCULATIONS HARD!

BASE ON:

a) A PRIORI "MICROSCOPIC" DESCRIPTION ✗

b) EXPTL. BEHAVIOR IN "CLASSICAL" LIMIT ✓


0·5 mm



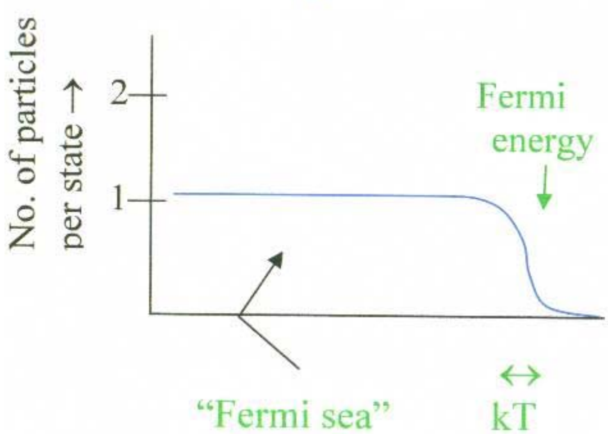
PHYSICS OF SUPERCONDUCTIVITY

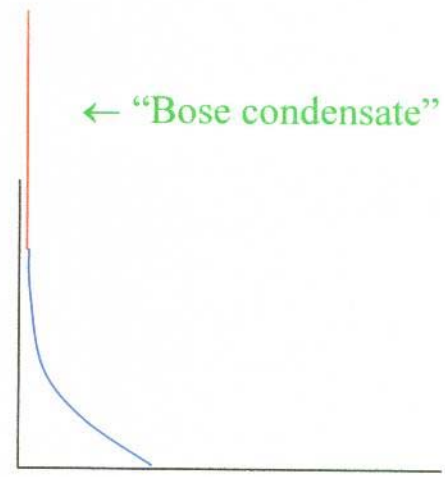
"Spin" of elementary particles $= \frac{n}{2}\,\hbar$

$0, 1, 2....$ bosons

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

At low temperatures:





Electrons in metals: spin ½ ⇒ fermions

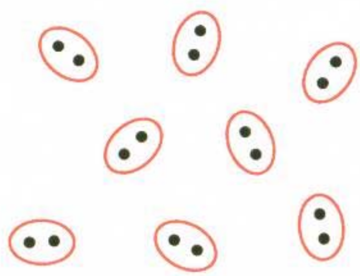
But a compound object consisting of an even no.

of fermions has spin 0, 1, 2 … ⇒ boson.

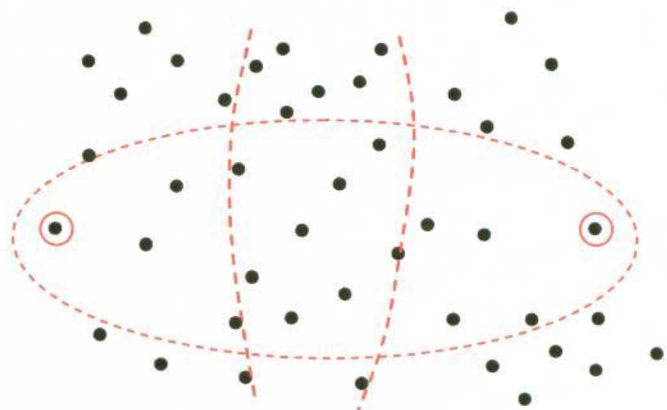
(Ex: $2p + 2n + 2c = {}^4He$ atom)

⇒ can undergo Bose condensation

Pairing of electrons:



"di-electronic molecules"

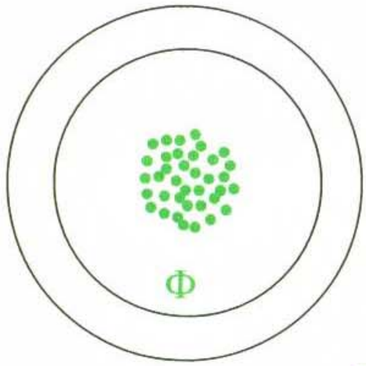


Cooper Pairs

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):

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

integer (n)

"flux quantum" (Φ_o) h/2e

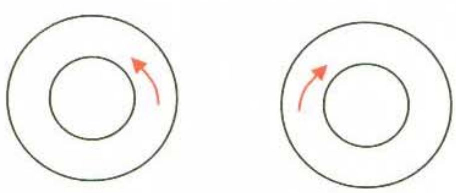
$E \propto K^2$

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

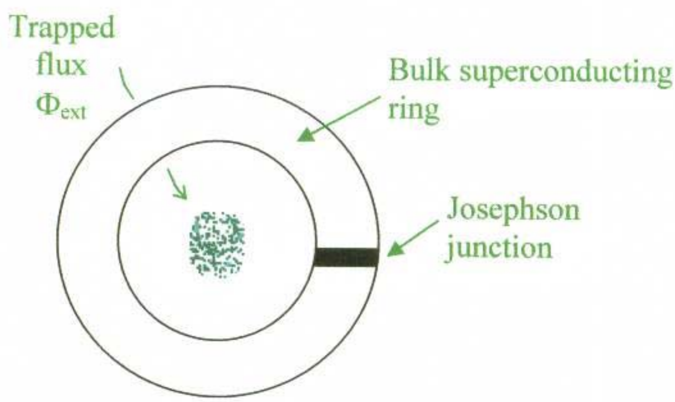
Or all pairs rotate anticlockwise

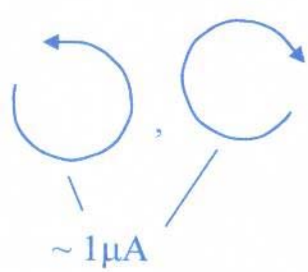
Note: state with 50% ↖ and 50% ↗

strongly forbidden by energy considerations

The Search for QIMDS (cont.)

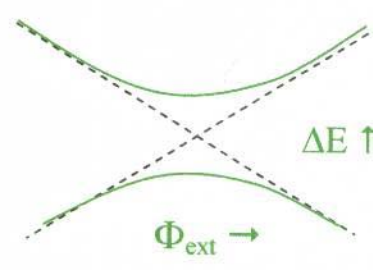
Josephson circuits





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

Evidence: (a) spectroscopic:
(SUNY, Delft 2000)



(b) real-time oscillations (like NH_3)

between ↺ and ↻

(Saclay 2002, Delft 2003) $(Q_\varphi \sim 50\text{-}350)$

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	$\sim 10^6$
[SQUIDS	$\sim 10^{10}$]

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.