SCHRÖDINGER'S CAT AND HER LABORATORY COUSINS

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1st Erwin Schrödinger Lecture
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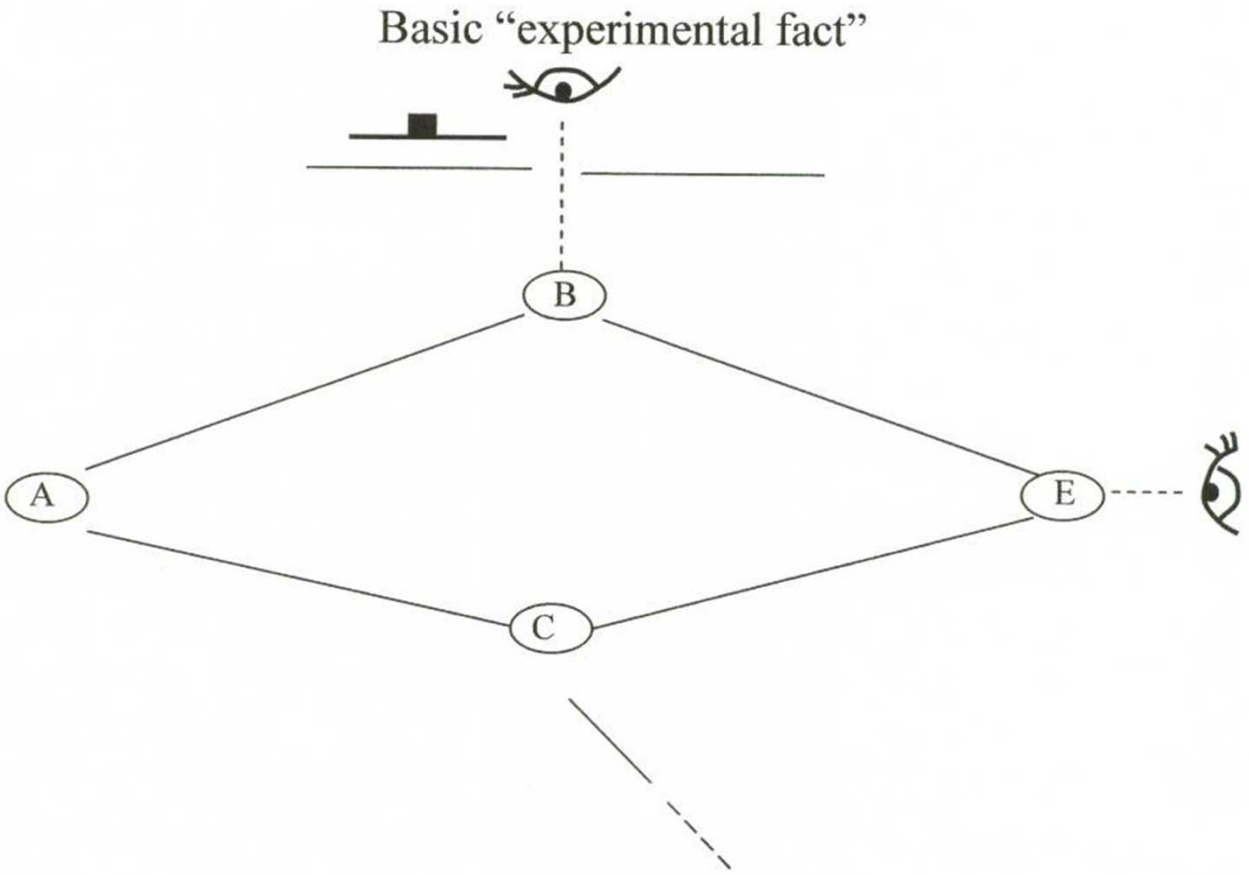


Experiment:

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. $\left(A \rightarrow \left\{\frac{B}{C}\right\} \rightarrow E\right)$ $(\equiv \text{“}P_{B \text{ or } C}\text{”})$

Result:

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

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

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

B. Don't look:

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

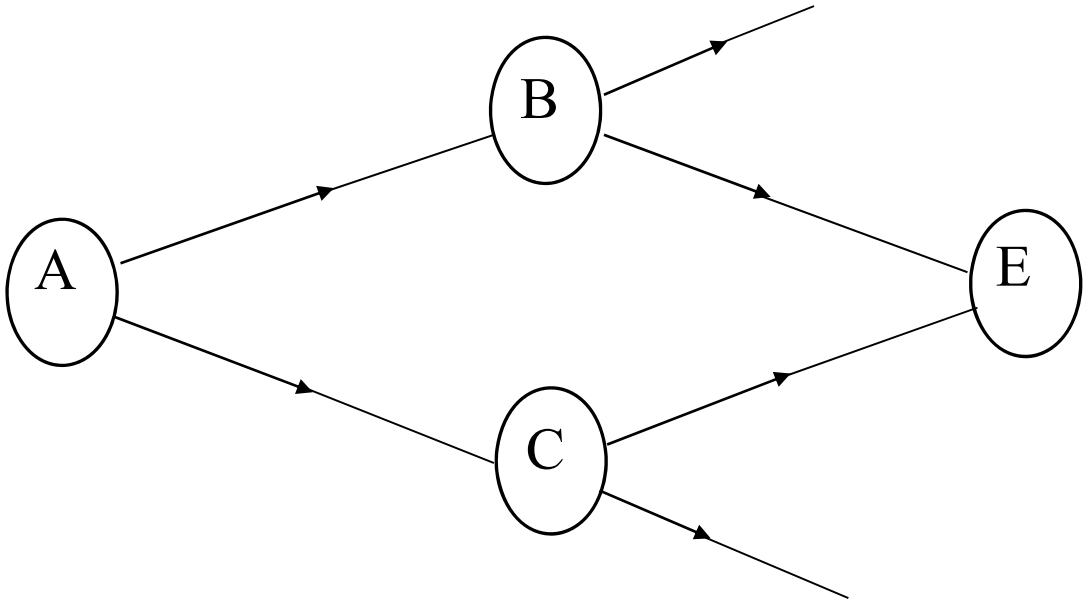
In fact, can have:

$P_B \neq 0$, $P_C \neq 0$, but $P_{B \text{ or } C} = 0$!
("total destructive interference")

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"

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

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

↑

"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 $-A_B^2 = 0$

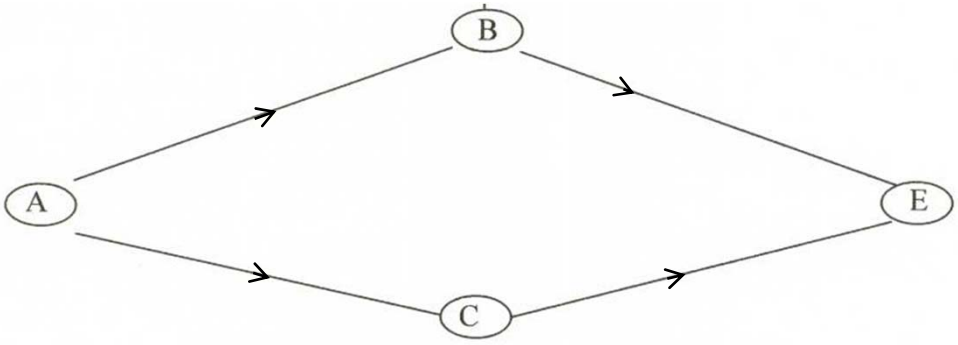
so

$$\overline{P}_{B\text{ or }C} = P_B + P_C \quad \leftarrow \text{“COMMON SENSE” RESULT,}$$

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

CONCLUSION: IF $A_B = A_C$ AT RANDOM, ALL EXPERIMENTAL RESULTS “AS IF” EACH SYSTEM REALIZES <u>EITHER</u> B <u>OR</u> C.

Interpretation of QM probability amplitudes:

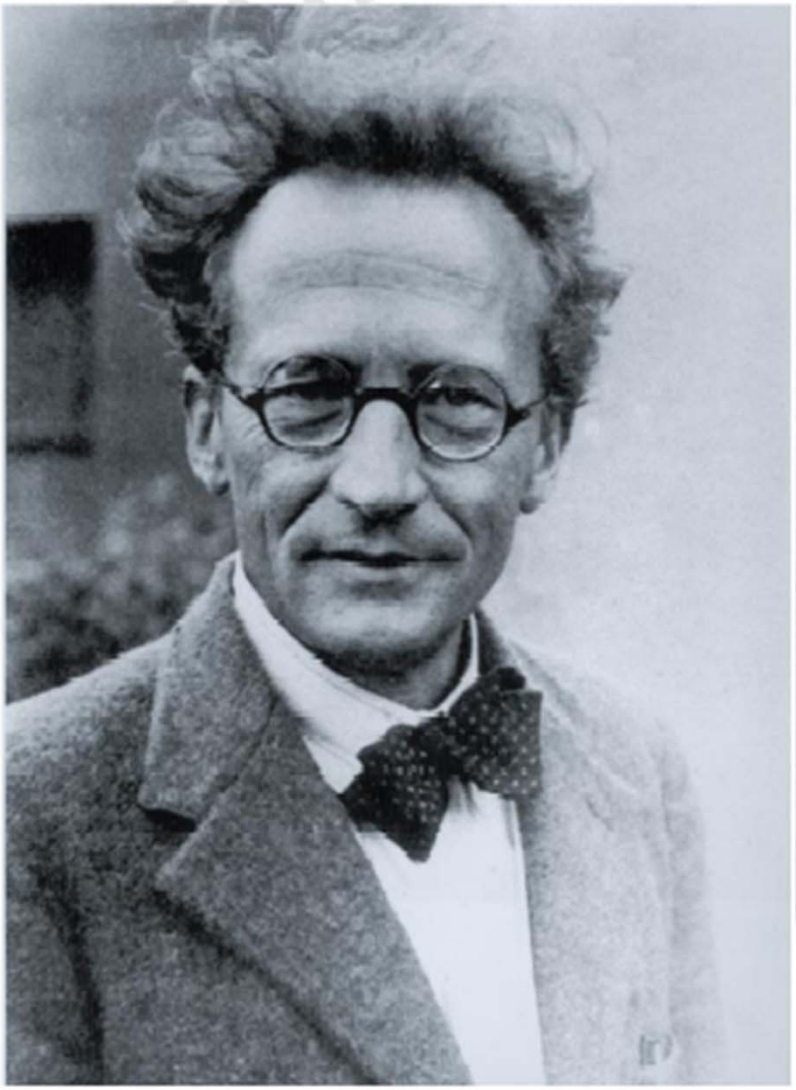


1. Directly from experimental data (interference): in experiment, not true that each atom realizes either B or C.

2. In QM formalism, interference is a result of simultaneous nonzero values of amplitudes A_B, A_C.

Natural inference:

whenever A_B, A_C are simultaneously nonzero, not true that each system realizes either B or C.



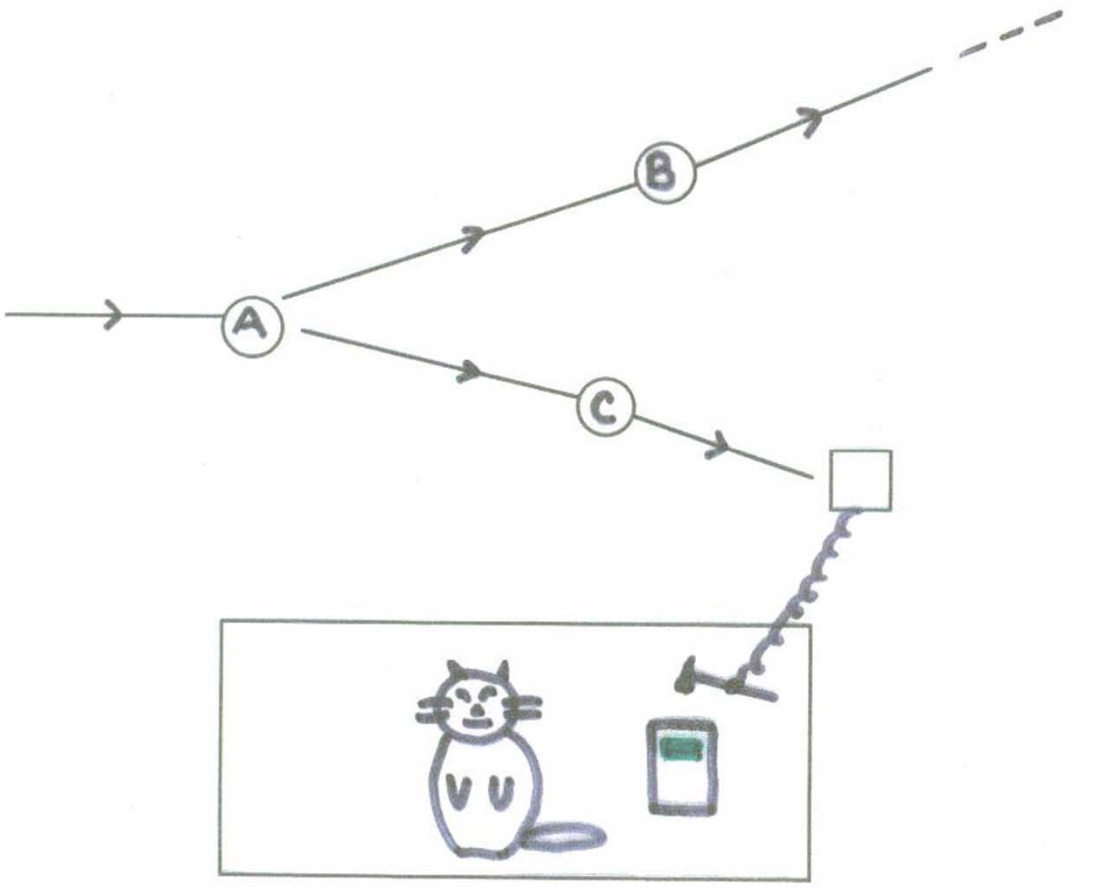
Verwaschenheit nicht. Die austretende Partikel wird, wenn man anschaulich deuten will, als Kugelwelle beschrieben, die nach allen Richtungen und fortwährend vom Kern emaniert und einen benachbarten Leuchtschirm fortwährend in seiner ganzen Ausdehnung trifft. Der Schirm aber zeigt nicht etwa ein beständiges mattes Flächenleuchten, sondern blitzt in *einem* Augenblick an *einer* Stelle auf — oder, um der Wahrheit die Ehre zu geben, er blitzt bald hier, bald dort auf, weil es unmöglich ist, den Versuch mit bloß einem einzigen radioaktiven Atom auszuführen. Benützt man statt des Leuchtschirms einen räumlich ausgedehnten Detektor, etwa ein Gas, das von den α-Teilchen ionisiert wird, so findet man die Ionenpaare längs geradliniger Kolonnen angeordnet[1], die rückwärts verlängert das radioaktive Materiekörnchen treffen, von dem die α-Strahlung ausgeht (C.T.R. Wilsonsche Bahnspuren, durch Nebeltröpfchen sichtbar gemacht, die auf den Ionen kondensieren).

Man kann auch ganz burleske Fälle konstruieren. Eine Katze wird in eine Stahlkammer gesperrt, zusammen mit folgender Höllenmaschine (die man gegen den direkten Zugriff der Katze sichern muß): in einem Geigerschen Zählrohr befindet sich eine winzige Menge radioaktiver Substanz, *so* wenig, daß im Lauf einer Stunde *vielleicht* eines von den Atomen zerfällt, ebenso wahrscheinlich aber auch keines; geschieht es, so spricht das Zählrohr an und betätigt über ein Relais ein Hämmerchen, das ein Kölbchen mit Blausäure zertrümmert. Hat man dieses ganze System eine Stunde lang sich selbst überlassen, so wird man sich sagen, daß die Katze noch lebt, *wenn* inzwischen kein Atom zerfallen ist. Der erste Atomzerfall würde sie vergiftet haben. Die ψ-Funktion des ganzen Systems würde das so zum Ausdruck bringen, daß in ihr die lebende und die tote Katze (s. v. v.) zu gleichen Teilen gemischt oder verschmiert sind.

Das Typische an diesen Fällen ist, daß eine ursprünglich auf den Atombereich beschränkte Unbestimmtheit sich in grobsinnliche Unbestimmtheit umsetzt, die sich dann durch direkte Beobachtung *entscheiden* läßt. Das hindert uns, in so naiver Weise ein „verwaschenes Modell" als Abbild der Wirklichkeit gelten zu lassen. An sich enthielte es nichts Unklares oder Widerspruchsvolles. Es ist ein Unterschied zwischen einer verwackelten oder unscharf eingestellten Photographie und einer Aufnahme von Wolken und Nebelschwaden.

(Fortsetzung folgt.)

[1] Zur Veranschaulichung kann Fig. 5 oder 6 auf S. 375 des Jg. 1927 dieser Zeitschrift dienen; oder auch Fig. 1, S. 734 des vorigen Jahrganges (1934), da sind es aber Bahnspuren von Wasserstoffkernen.



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

ampl. (cat alive) ≠ 0

ampl. (cat dead) ≠ 0

Some "resolutions" of the Cat paradox

(a) Assume quantum mechanics is universal

(i) Extreme statistical

(ii) "many-worlds"

(iii) "Orthodox" resolution:

Recall

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

If $A_C = \pm A_B$ at random,

← averages to zero

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

i.e., everything "as if" each system realized either B or 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?

More "resolutions"

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

e.g. GRWP* theory

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

- universal, non-quantum mechanical "noise" background

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

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

- rate of evolution $\propto$ N

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

"macrorealism": at level of "everyday life", one state or the other always realized.

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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
- isolation from outside world
- very low intrinsic dissipation

} $\Rightarrow$ decoherence ineffective

QM CALCULATIONS HARD!

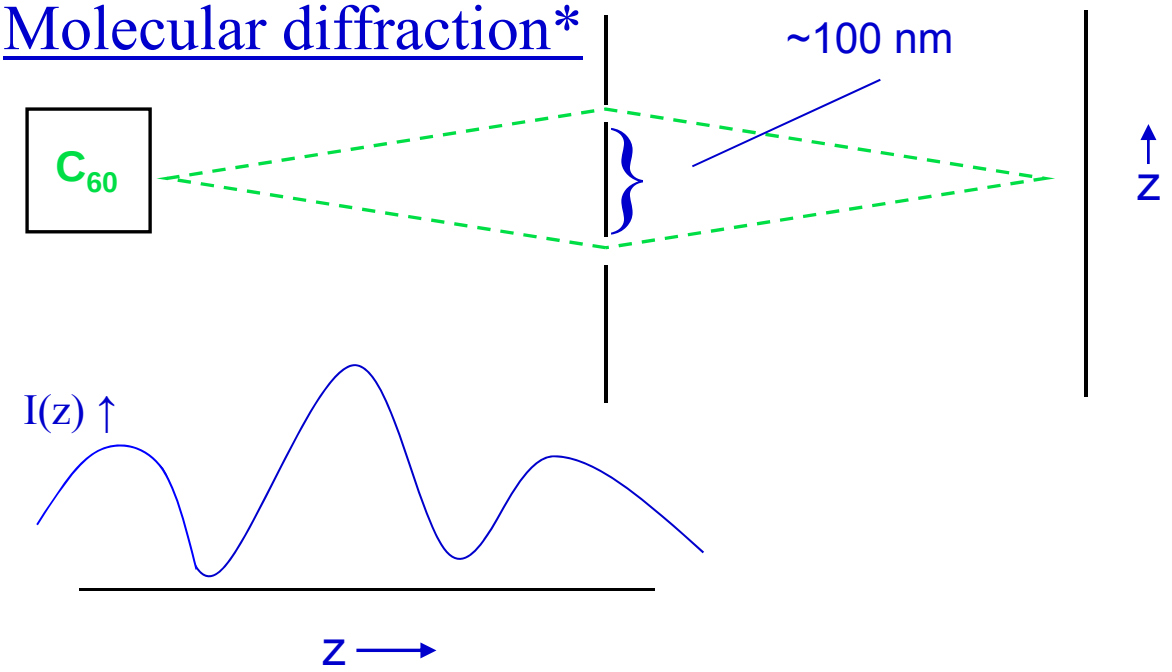
BASE ON:

a) A PRIORI "MICROSCOPIC" DESCRIPTION ✗

b) EXPTL. BEHAVIOR IN "CLASSICAL" LIMIT ✓

The most direct extension of microscopic experiments:

Molecular diffraction*



Note:

(a.) Beam does not have to be monochromated or collimated

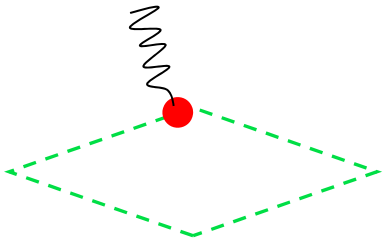
(b.) "Which-way" effects?

Oven is at 900–1000 K

⇒ many vibrational modes excited

4 modes infrared active ⇒

absorb/emit several radiation quanta on passage through apparatus!



Why doesn't this destroy interference?

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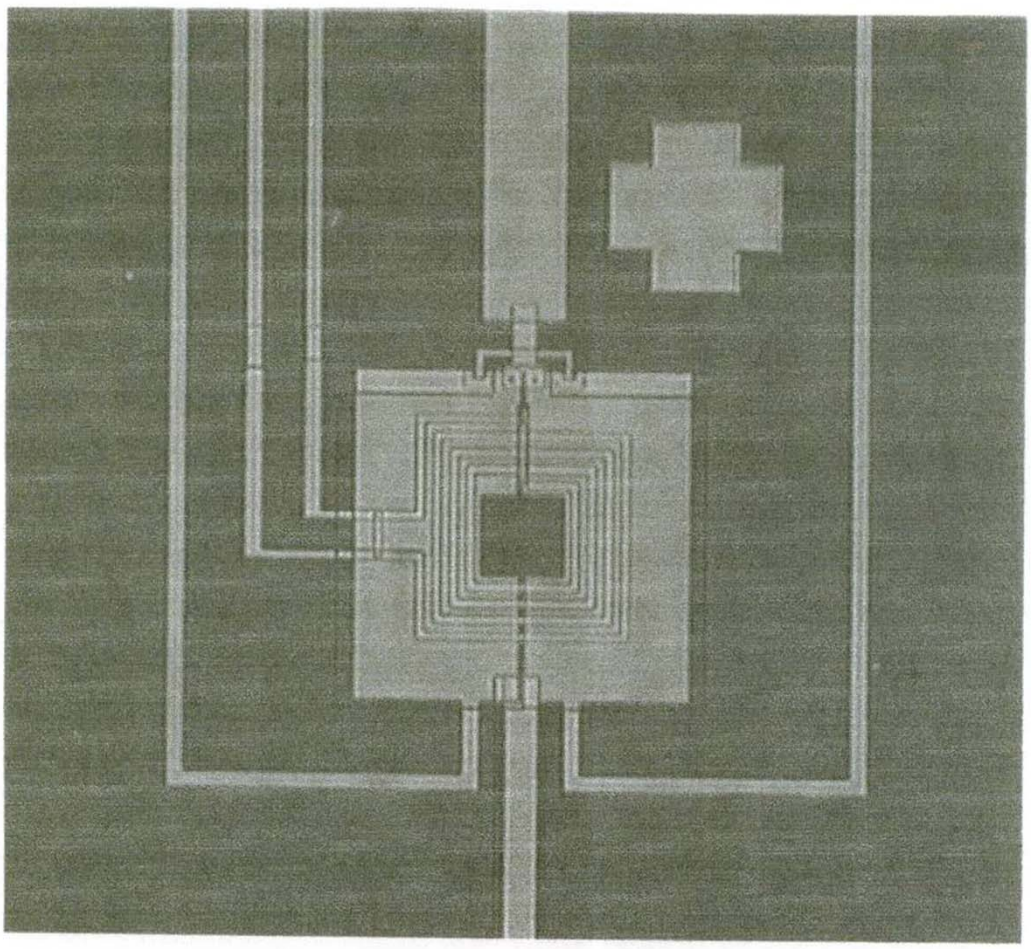
*Arndt et al., Nature *401*, 680 (1999); Nairz et al., Am. J. Phys. *71*, 319 (2003).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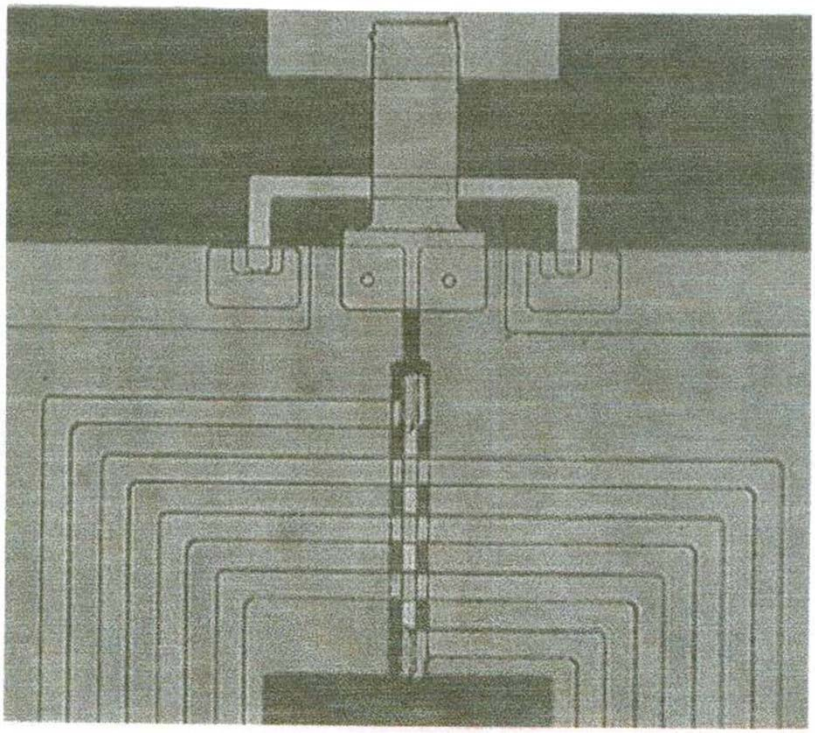
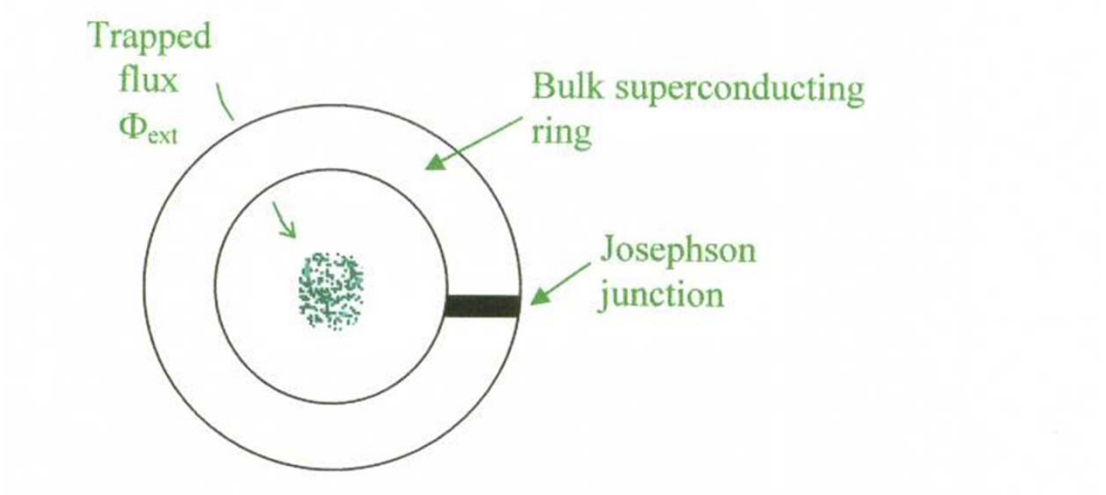
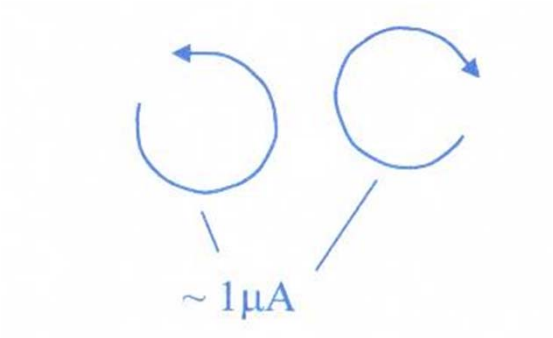


"Flux qubit": schematic



Experimental fact: at the "classical" level, system has two macroscopically distinct states:



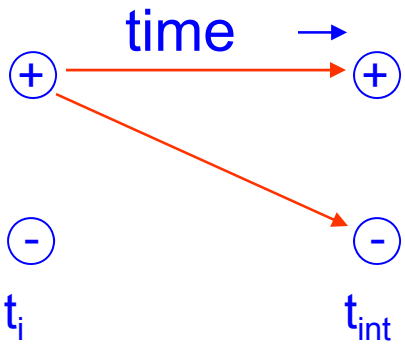
Whenever observed, system appears always to be in one or other of these two states.

What if it is not observed?

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

i.e. quantum superposition of macroscopically distinct states?

How would we tell? (Denote ($|\circlearrowleft\rangle \equiv \oplus$, $|\circlearrowright\rangle \equiv \ominus$)

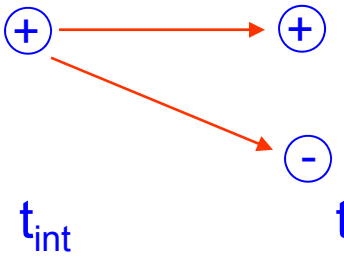


What is state of system at time t_{int}?

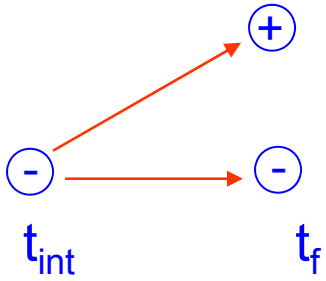
(a) it is definitely either ⊕ or ⊖

(b) it is a quantum superposition of ⊕ and ⊖

According to QM:

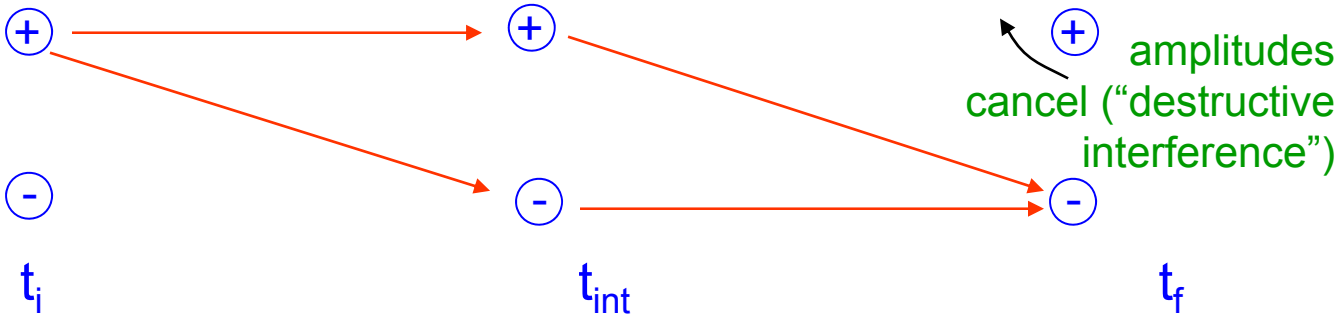


and



so if (a), then at t_f probability of ⊕ ≠ 0

If (b), with correct choice of times etc.,



So for (b), at t_f probability of ⊕ = 0.

Experiments favor (b)!

So, everything consistent with QM

superposition at t_{int}…

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	~10^4 - 10^{10}	} depends on definition of "involved"
Cf: smallest visible dust particle	~10^3 - 10^{15}	

By most definitions, states of SQUID more "macroscopically distinct" than those of dust particles!

Where to go next?

- Larger/more complex objects
- Nanomechanical/optomechanical systems
- 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. ?!