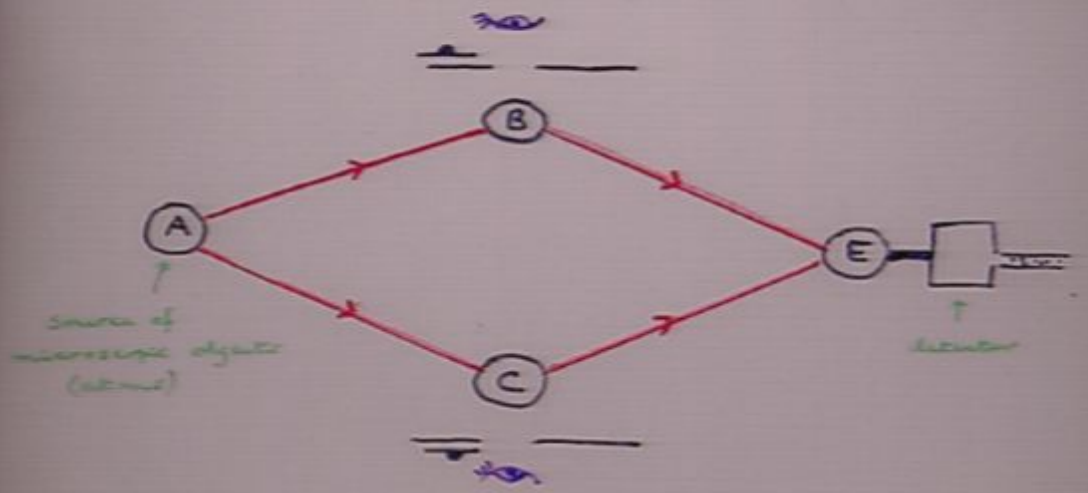
Title: Foundations and Interpretation of Quantum Theory - Lecture 18

Date: Mar 23, 2010 02:30 PM

URL: http://pirsa.org/10030007

Abstract:

Interference — The Raw Data



$P_B \equiv$ prob. (no. arriving at E / total no. emitted) with only path B open

$P_C \equiv$ prob. with only path C open

$P_{B \text{ or } C} \equiv$ prob. with **both** paths open

With "inspection":

each atom (etc.) follows **either** path B **or** path C

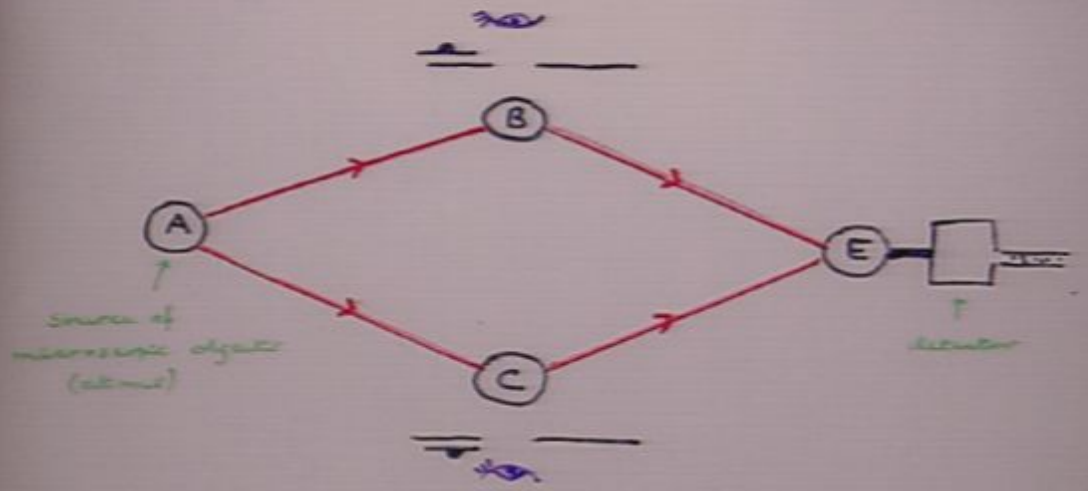
$P_{B \text{ or } C} = P_B + P_C$ ("common sense" result)

Without "inspection":

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

Prima facie conclusion: in absence of "inspection":
We **cannot** say that each atom followed **either** path B **or** path C. (cf: Bohm)

Interference — The Raw Data



$P_B \equiv$ prob. (no. arriving at E / total no. emitted) with only path B open

$P_C \equiv$ prob. with only path C open

$P_{B \text{ or } C} \equiv$ prob. with **both** paths open

With "inspection":

each atom (etc.) follows **either** path B **or** path C

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

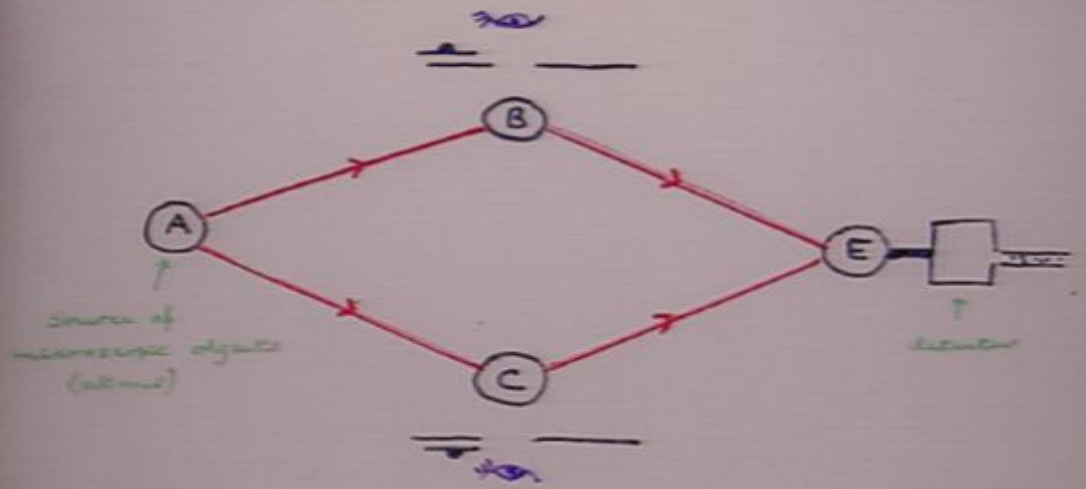
Without "inspection":

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

Prima facie conclusion: in absence of "inspection", We **cannot** say that each atom followed **either** path B **or** path C. (Q: Bohm)

Interference — The Raw Data

IQC 1.1



$P_B \equiv$ prob. (no. arriving at E / total no. emitted) with only path B open

$P_C \equiv$ prob. with only path C open

$P_{B \text{ or } C} \equiv$ prob. with **both** paths open

With "inspection":

each atom (etc.) follows **either** path B **or** path C

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

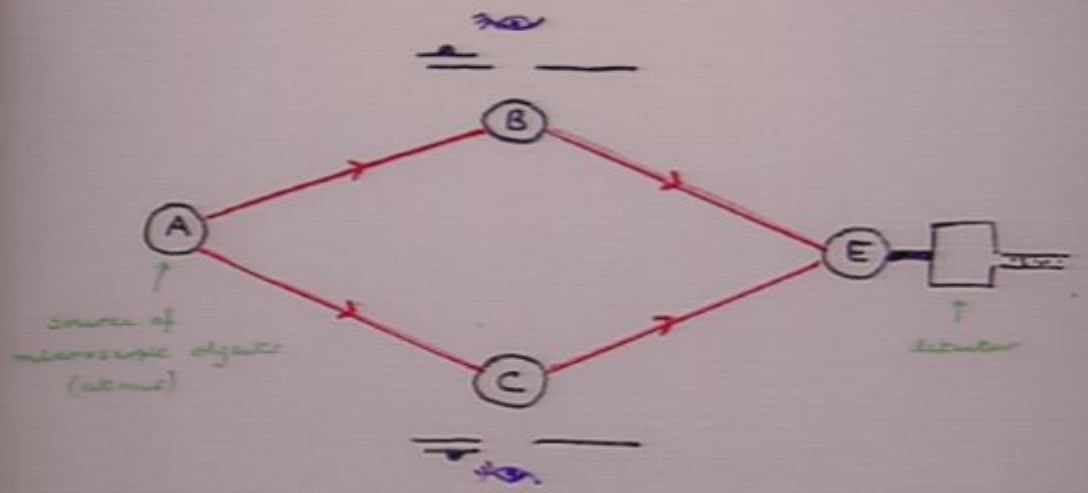
Without "inspection":

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

Prima facie conclusion: in absence of "inspection", We **cannot** say that each atom followed **either** path B **or** path C. (Q: Bohm)

Interference — The Raw Data

IQC 1.1



$P_B \equiv$ prob. (no. arriving at E / total no. emitted) with only path B open

$P_C \equiv$ prob. with only path C open

$P_{B \text{ or } C} \equiv$ prob. with **both** paths open

With "inspection":

each atom (etc.) follows **either** path B **or** path C

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

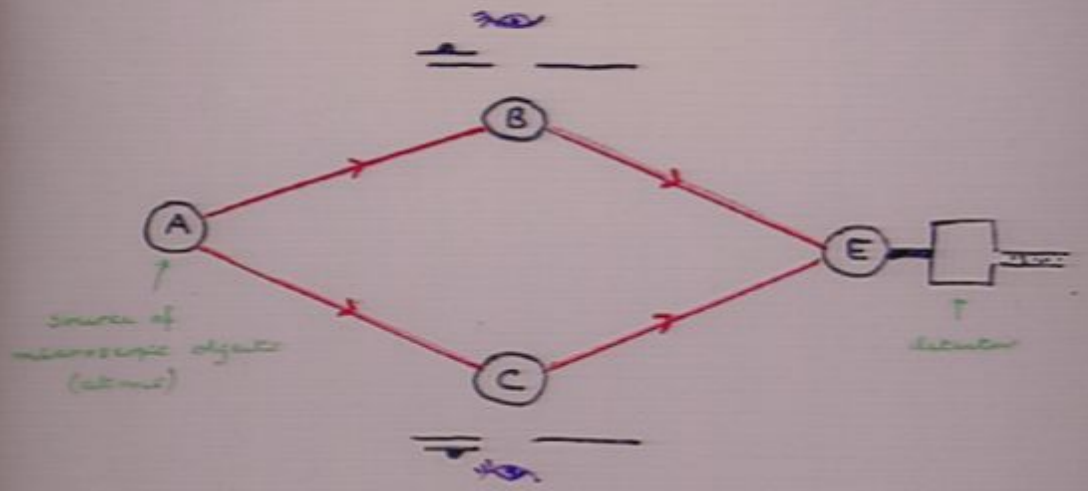
Without "inspection":

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

Prima facie conclusion: in absence of "inspection", We cannot say that each atom followed either path B or path C. (Q: Bohm)

Interference — The Raw Data

IQC 1.1



$P_B \equiv$ prob. (no. arriving at E / total no. emitted) with only path B open

$P_C \equiv$ prob. with only path C open

$P_{B \text{ or } C} \equiv$ prob. with **both** paths open

With "inspection":

each atom (etc.) follows **either** path B **or** path C

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

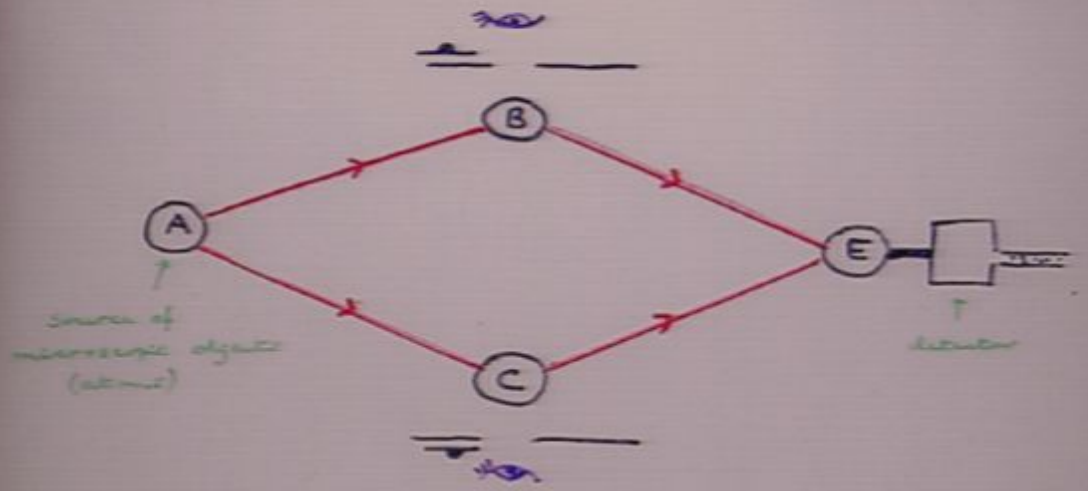
Without "inspection":

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

Prima facie conclusion: in absence of "inspection", We **cannot** say that each atom followed **either** path B **or** path C. (Q: Bohm)

Interference — The Raw Data

IIEC 1.1



$P_B \equiv$ prob. (no. arriving at E / total no. emitted) with only path B open

$P_C \equiv$ prob. with only path C open

$P_{B \text{ or } C} \equiv$ prob. with **both** paths open

With "inspection":

each atom (etc.) follows **either** path B **or** path C

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

Without "inspection":

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

Prima facie conclusion: in absence of "inspection", We cannot say that each atom followed either path B or path C. (Q: Bohm)

Interference — Account given by QM

$$A_{tot} = \sum_i A_i \quad , \quad P_{tot} = |A_{tot}|^2$$

(sum over possible paths)

In our case:

$$P_B = |A_B|^2 , \qquad P_C = |A_C|^2 .$$

$$P_{B \text{ or } C} = |A_B + A_C|^2 = |A_B|^2 + |A_C|^2 + 2\,\mathrm{Re}(A_B^* A_C)$$

$\Rightarrow$

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

("classical" result) (interference term)

Note: It is a necessary and sufficient* condition to get nonzero interference effects that the amplitudes A_B and A_C be simultaneously nonzero.

Thus, at the microlevel:

- A_B, A_C simultaneously nonzero $\Rightarrow$ interference
- interference $\Rightarrow$ no "definite choice"

$\Rightarrow$ A_B, A_C simultaneously nonzero $\Rightarrow$ no definite choice

* Except for special case $A_B^* A_C = \text{pure Im.}$

INTERFERENCE — ACCOUNT GIVEN BY QM

$$A_{tot} = \sum_i A_i \quad , \quad P_{tot} = |A_{tot}|^2$$

(sum over possible paths)

In our case:

$$P_B = |A_B|^2 . \qquad P_C = |A_C|^2 .$$

$$P_{B\text{ or }C} = |A_B + A_C|^2 = |A_B|^2 + |A_C|^2 + 2\,\mathrm{Re}(A_B^* A_C)$$

$\Rightarrow$

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

("common-sense" result) (interference term)

Note: It is a necessary and sufficient* condition to get nonzero interference effects that the amplitudes A_B and A_C be simultaneously nonzero.

Thus, at the microlevel:

- A_B, A_C simultaneously nonzero $\Rightarrow$ interference
- interference $\Rightarrow$ no "definite choice"

$\Rightarrow$

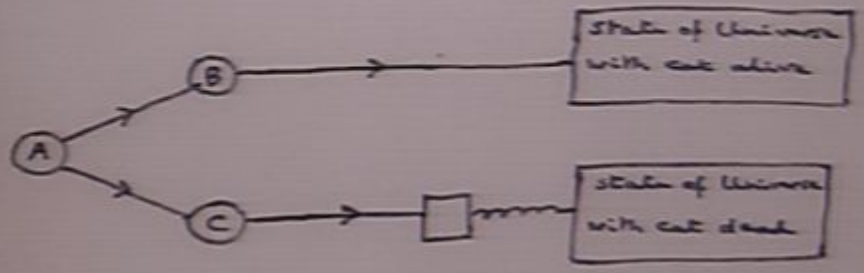
A_B, A_C simultaneously nonzero $\Rightarrow$ no definite choice

* Except for special case $A_B^* A_C$ = pure Im.

Recap: At microlevel,

A_B, A_C simultaneously nonzero $\Rightarrow$ neither option B nor option C "selected".

Now, following Schrödinger, extrapolate formal QM description to macrolevel:



Inductable consequence of linear + unitary nature of QM

If: (i) (ii)

$A_B \to \Psi_B$
$A_C \to \Psi_C$

(macroscopically distinct final states of Universe)

then inevitably

$$\lambda A_B + \mu A_C \to \lambda \Psi_B + \mu \Psi_C$$

$\Rightarrow$ if microscopic amplitudes A_B, A_C simultaneously nonzero, then

macroscopic amplitudes Ψ_B, Ψ_C simultaneously nonzero!

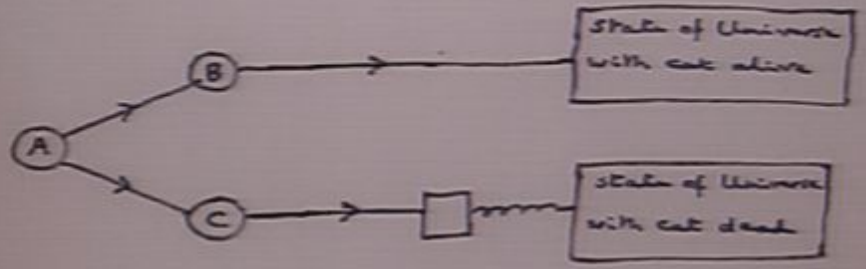
$\Rightarrow$ neither macroscopic state "selected" ??

REALIZATION ("MEASUREMENT") PARADOX

Recap: At microlevel,

A_B, A_C simultaneously nonzero $\Rightarrow$ neither option B nor option C "selected".

Now, following Schrödinger, extrapolate formal QM description to macrolevel:



Inductable consequence of linear + unitary nature of QM

If:

$A_B \rightarrow \Psi_B$

$A_C \rightarrow \Psi_C$

(macroscopically distinct final states of Universe)

then inevitably

$$\lambda A_B + \mu A_C \rightarrow \lambda \Psi_B + \mu \Psi_C$$

$\Rightarrow$ if microscopic amplitudes A_B, A_C simultaneously nonzero, then

macroscopic amplitudes Ψ_B, Ψ_C simultaneously nonzero!

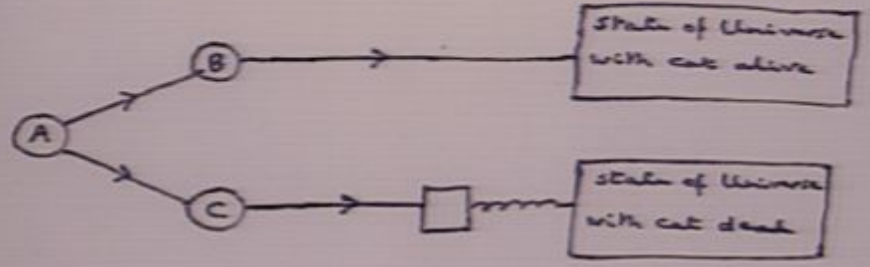
$\Rightarrow$ neither macroscopic state "selected" ??

REALIZATION ("MEASUREMENT") PARADOX

Recap: At microlevel,

A_B, A_C simultaneously nonzero $\Rightarrow$ neither option B nor option C "selected".

Now, following Schrödinger, extrapolate formal QM description to macrolevel:



Inelectable consequence of linear + unitary nature of QM

If:

$A_B \longrightarrow \Psi_B$

$A_C \longrightarrow \Psi_C$

} (macroscopically distinct) final states of Universe

then inevitably

$$\lambda A_B + \mu A_C \longrightarrow \lambda \Psi_B + \mu \Psi_C$$

$\Rightarrow$ if microscopic amplitudes A_B, A_C simultaneously nonzero, then

macroscopic amplitudes Ψ_B, Ψ_C simultaneously nonzero!

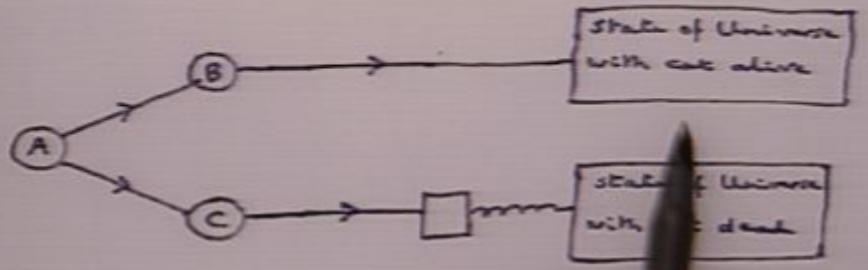
$\Rightarrow$ neither macroscopic state "selected" ??

REALIZATION ("MEASUREMENT") PARADOX

Recap: At microlevel,

A_B, A_C simultaneously nonzero $\Rightarrow$ neither option B nor option C "selected".

Now, following Schrödinger, extrapolate formal QM description to macrolevel:



Inductable consequence of linear + unitary nature of QM

If:

$$A_B \rightarrow \Psi_B$$
$$A_C \rightarrow \Psi_C$$

(macroscopic difference)

then inevitably

$$\lambda A_B + \mu A_C \rightarrow \lambda \Psi_B + \mu \Psi_C$$

$\Rightarrow$ if microscopic amplitudes

nonzero, then

macroscopic amplitudes

nonzero

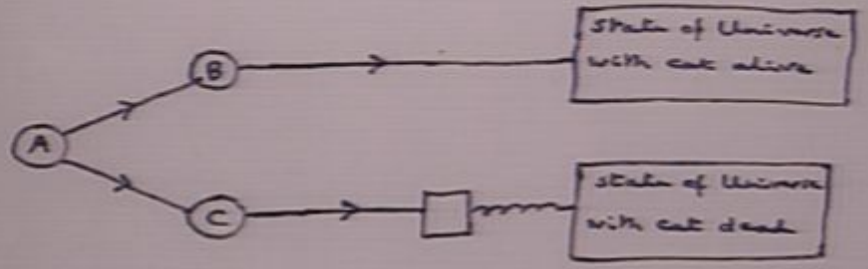
$\Rightarrow$ neither

REALITY

Recap: At microlevel,

A_B, A_C simultaneously non-zero $\Rightarrow$ neither option B nor option C "selected".

Now, following Schrödinger, extrapolate formal QM description to macrolevel:



Inductable consequence of linear + unitary nature of QM

If:

$A_B \longrightarrow \Psi_B$

$A_C \longrightarrow \Psi_C$

} (macroscopically distinct) final state of Universe

then inevitably

$\lambda A_B + \mu A_C \longrightarrow \lambda\Psi_B + \mu\Psi_C$

$\Rightarrow$ if microscopic amplitudes A_B, A_C simultaneously non-zero, then

macroscopic amplitudes Ψ_B, Ψ_C simultaneously

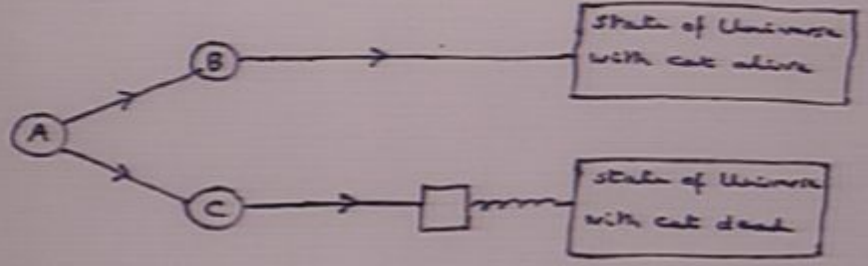
$\Rightarrow$ [illegible] state "selected" ??

[illegible] ENDENT") PARADOX

Recap: At microlevel,

A_B, A_C simultaneously nonzero $\Rightarrow$ neither option B nor option C "selected".

Now, following Schrödinger, extrapolate formal QM description to **macro**level:



Inductable consequence of linear + unitary nature of QM

If:

$$A_B \longrightarrow \Psi_B$$
$$A_C \longrightarrow \Psi_C$$

} (macroscopically distinct final states of Universe)

then inevitably

$$\lambda A_B + \mu A_C \longrightarrow \lambda\Psi_B + \mu\Psi_C$$

$\Rightarrow$ if microscopic amplitudes A_B, A_C simultaneously nonzero, then

macroscopic amplitudes Ψ_B, Ψ_C simultaneously nonzero!

$\Rightarrow$ neither macroscopic state "selected" ??

REALIZATION ("MEASUREMENT") PARADOX

Some "Solutions" of the Realization Paradox

IREC 1.4

(a) Assume QM is the whole truth about the physical Universe.

Then:

(1) statistical ("quantum-information-theoretic") interpretation (e.g. N.D. Mermin, Quantum Information Processing, 35, 239 (2001)):

The formalism of QM describes only our **state of information** about the world: amplitudes correspond to nothing "out there", at either micro- or macro-level.

Apparently internally consistent, but ...

(2) "many-worlds" (relative-state, Everett-Wheeler...) (e.g. D. Deutsch, Int. J. Theor. Physics 24, 1 (1985)): amplitudes correspond to physical reality, at both micro- **and** macro-level.

↑ : Schrödinger roulette ...

(3) Retroactive causality (cf. L.S. Schulman, Ann. Phys. 212, 315 (1991))

("consistent")

("inconsistent")

↑ : consistent with 2nd law?

Some "Solutions" of the Realization Paradox

REC 1.4

(a) Assume QM is the whole truth about the physical Universe.

Then:

(1) statistical ("quantum-information-theoretic") interpretation (e.g. N.D. Mermin, Quantum Information Processing, 35, 239 (2004)):

The formalism of QM describes only our **state of information** about the world: amplitudes correspond to nothing "out there", at either micro- or macro-level.

Apparently internally consistent, but ...

(2) "many-worlds" (relative-state, Everett-Wheeler...) (e.g. D. Deutsch, Int. J. Theor. Physics 24, 1 (1985)): amplitudes correspond to physical reality, at both micro- **and** macro-level.

↑ : Schrödinger roulette ...

(3) Retroactive causality (cf. L.S. Schulman, Ann. Phys. 212, 315 (1991))

("consistent")

("inconsistent")

↑: consistent with 2nd law?

"Solutions" based on hypothesis of universal validity of QM (unit.)

(4) "Orthodox" (decoherence) (e.g. W.H. Zurek, Rev. Mod. Phys. 75, 715 (2003))

Decoherence: "Universe" (U) = system (S) + environment (E)

quantum superposition:

$$\left.\begin{aligned}\psi &= \alpha\psi_1 + \beta\psi_2 \\ \Psi_E &= (\alpha\psi_1 + \beta\psi_2)\chi_0\end{aligned}\right\} \Rightarrow \hat{\rho}_S = \begin{pmatrix} |\alpha|^2 & \alpha^*\beta \\ \alpha\beta^* & |\beta|^2 \end{pmatrix}$$

Effect of S–E interaction:

$$\Psi_U = (\alpha\psi_1 + \beta\psi_2)\chi_0 \Rightarrow \alpha\psi_1\chi_1 + \beta\psi_2\chi_2.$$

$$(\chi_1, \chi_2) \cong 0$$

$$\Rightarrow \quad \hat{\rho}_S \equiv \mathrm{Tr}_E\, \hat{\rho}_U = \begin{pmatrix} |\alpha|^2 & 0 \\ 0 & |\beta|^2 \end{pmatrix}$$

$\Rightarrow$ probabilities for outcomes of all measurements on S as if state 1 (2) realized with prob. $|\alpha|^2$ ($|\beta|^2$)

So far, so good ....

$\Uparrow$: $\Rightarrow$ "each ind.! system actually realizes either state 1 or state 2" ??

(a) Bell's objection

(b) more seriously, GROSS LOGICAL FALLACY?

(does vanishing of evidence $\Rightarrow$ legitimacy of fundamental misinterpretation of meaning of formalism?)

"Solutions" based on hypothesis of universal validity of QM (unit.)

(+) "Orthodox" (decoherence) (e.g. W.H. Zurek, Rev. Mod. Phys. 75, 715 (2003))

Decoherence: "Universe" (U) = system (S) + environment (E)

quantum superposition:

$$\left.\begin{aligned}\psi &= \alpha\psi_1 + \beta\psi_2\\ \Psi_E &= (\alpha\psi_1 + \beta\psi_2)\chi_0\end{aligned}\right\} \Rightarrow \hat{\rho}_S = \begin{pmatrix} |\alpha|^2 & \alpha^*\beta \\ \alpha\beta^* & |\beta|^2 \end{pmatrix}$$

Effect of S-E interaction:

$$\Psi_U = (\alpha\psi_1 + \beta\psi_2)\chi_0 \Rightarrow \alpha\psi_1\chi_1 + \beta\psi_2\chi_2.$$

$$(\chi_1, \chi_2) \cong 0$$

$$\Rightarrow \quad \hat{\rho}_S \equiv \mathrm{Tr}_E\, \hat{\rho}_U = \begin{pmatrix} |\alpha|^2 & 0 \\ 0 & |\beta|^2 \end{pmatrix}$$

$\Rightarrow$ predictions for outcomes of all measurements on S as if state 1 (2) realized with prob. $|\alpha|^2$ ($|\beta|^2$)

("mixture" state)

So far, so good....

$\Uparrow$: $\Rightarrow$ "each ind.l system actually realizes either state 1 or state 2" ??

(a) Bell's objection

(b) more seriously, GROSS LOGICAL FALLACY?

(does vanishing of evidence $\Rightarrow$ legitimacy of fundamental misinterpretation of meaning of formalism?)

"Solutions" based on hypothesis of universal validity of QM (cont.)

(+) "Orthodox" (decoherence) (e.g. W.H. Zurek, Rev. Mod. Phys 75, 715 (2003))

Decoherence: "Universe" (U) = system (S) + environment (E)

quantum superposition:

$$\left.\begin{aligned}\Psi &= \alpha\psi_1 + \beta\psi_2 \\ \Psi &= (\alpha\psi_1 + \beta\psi_2)X_0\end{aligned}\right\} \Rightarrow \hat{\rho}_S = \begin{pmatrix} |\alpha|^2 & \alpha^*\beta \\ \alpha\beta^* & |\beta|^2 \end{pmatrix}$$

Effect of S-E interaction:

$$\Psi_U = (\alpha\psi_1 + \beta\psi_2)X_0 \Rightarrow \alpha\psi_1 X_1 + \beta\psi_2 X_2.$$

$$(X_1, X_2) \cong 0$$

$$\Rightarrow \quad \hat{\rho}_S \equiv \mathrm{Tr}_E\, \hat{\rho}_U = \begin{pmatrix} |\alpha|^2 & 0 \\ 0 & |\beta|^2 \end{pmatrix}$$

$\Rightarrow$ predictions for outcomes of all measurements on S as if state 1 (2) realized with prob. $|\alpha|^2$ ($|\beta|^2$) ("many worlds" result)

So far, so good....

↑: $\Rightarrow$ "each ind.l system actually realizes either state 1 or state 2" ??

(a) Bell's objection

(b) more seriously, GROSS LOGICAL FALLACY?

(does vanishing of evidence $\Rightarrow$ legitimacy of fundamental interpretation of meaning of formalism?)

"Solutions" based on hypothesis of universal validity of QM (cont.)

(+) "Orthodox" (decoherence) (e.g. W.H. Zurek, Rev. Mod. Phys 75, 715 (2003))

Decoherence: "Universe" (U) = system (S) + environment (E)

quantum superposition:

$$\left.\begin{aligned}\Psi &= \alpha\psi_1 + \beta\psi_2 \\ \Psi &= (\alpha\psi_1 + \beta\psi_2)X_0\end{aligned}\right\} \Rightarrow \hat{\rho}_S = \begin{pmatrix} |\alpha|^2 & \alpha^*\beta \\ \alpha\beta^* & |\beta|^2 \end{pmatrix}$$

↑ state of env.

Effect of S-E interaction:

$$\Psi_U = (\alpha\psi_1 + \beta\psi_2)X_0 \Rightarrow \alpha\psi_1 X_1 + \beta\psi_2 X_2.$$

$$(X_1, X_2) \cong 0$$

$$\Rightarrow \quad \hat{\rho}_S \equiv \mathrm{Tr}_E \hat{\rho}_U = \begin{pmatrix} |\alpha|^2 & 0 \\ 0 & |\beta|^2 \end{pmatrix}$$

⇒ predictions for outcomes of all measurements on S as if state 1 (2) realized with prob. $|\alpha|^2$ ($|\beta|^2$) ("mixed state" ensemble)

So far, so good....

↑: ⇒ "each ind.l system actually realizes either state 1 or state 2" ??

(a) Bell's objection

(b) more seriously, GROSS LOGICAL FALLACY?

(does vanishing of evidence ⇒ legitimacy of fundamental misinterpretation of meaning of formalism?)

"Solutions" based on hypothesis of universal validity of QM (cont.)

(a) "Orthodox" (decoherence) (e.g. W.H. Zurek, Rev. Mod. Phys 75, 715 (2003))

Decoherence: "Universe" (U) ≡ system (S) + environment (E)

quantum superposition:

$$\left.\begin{aligned}\psi &= \alpha\psi_1 + \beta\psi_2 \\ \Psi &= (\alpha\psi_1 + \beta\psi_2)\chi_0\end{aligned}\right\} \Rightarrow \hat{\rho}_S = \begin{pmatrix} |\alpha|^2 & \alpha^*\beta \\ \alpha\beta^* & |\beta|^2 \end{pmatrix}$$

Effect of S-E interaction:

$$\Psi_U = (\alpha\psi_1 + \beta\psi_2)\chi_0 \Rightarrow \alpha\psi_1\chi_1 + \beta\psi_2\chi_2.$$

$$(\chi_1, \chi_2) \cong 0$$

$$\Rightarrow \quad \hat{\rho}_S \equiv \mathrm{Tr}_E\, \hat{\rho}_U = \begin{pmatrix} |\alpha|^2 & 0 \\ 0 & |\beta|^2 \end{pmatrix}$$

⇒ predictions for outcomes of all measurements on S as if state 1 (2) realized with prob. $|\alpha|^2$ ($|\beta|^2$) ("many worlds")

So far, so good....

↑: ⇒ "each ind.t system actually realizes either state 1 or state 2" ??

(a) Bell's objection

(b) more seriously, GROSS LOGICAL FALLACY?

(does vanishing of evidence ⇒ legitimacy of fundamental misinterpretation of meaning of formalism?)

CAS 9 ©
=Rec 1.6

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"

*Ghirardi, Rimini, Weber, Pearle (see e.g. P. Pearle, Phys. Rev. A 39, 2277 (1989))

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" ($>10^{-5}$ 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"

*Ghirardi, Rimini, Weber, Pearle (see e.g. P. Pearle, Phys. Rev. A 39, 2277 (1989))

Q: Is it possible to discriminate experimentally between hypotheses (A) and (B) (at a given level of "macroscopieness")?

A: Yes, if and only if we can observe Quantum Interference of Macroscopically Distinct States (QIMDS).

What is appropriate measure of "macroscopieness" ("Schrödinger's cattiness") of a quantum superposition?

†: Definition should not make nonexistence of QIMDS a tautology!

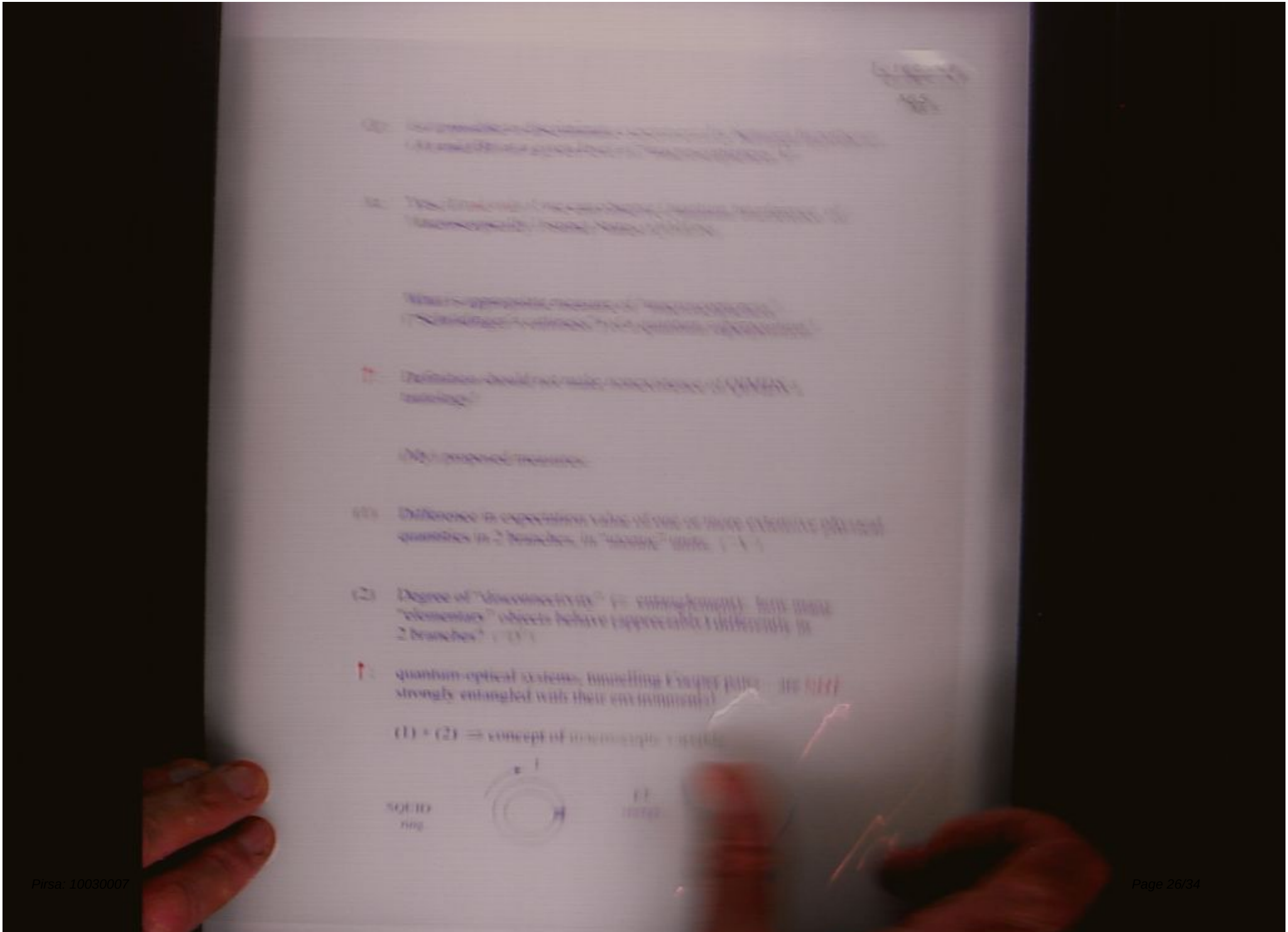
(My) proposed measures:

(1) Difference in expectation value of one or more extensive physical quantities in 2 branches, in "atomic" units. ("Δ")

(2) Degree of "disconnectivity" (≡ entanglement): how many "elementary" objects behave (appreciably) differently in 2 branches? ("D")

†: quantum-optical systems, tunnelling Cooper pairs...are NOT strongly entangled with their environments!

(1) + (2) ⇒ concept of macroscopic variable.



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" ($>10^{-5}$ 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"

*Ghirardi, Rimini, Weber, Pearle (see e.g. P. Pearle, Phys. Rev. A 39, 2277 (1989))

PROGRAM:

Stage 1: Circumstantial tests of applicability of QM to macrovariables.

Stage 2: Observation (or not!) of QIMDS given QM'I interpretation of raw data.

Stage 3: EITHER (a) exclude hypothesis B (macro-realism) independently of interpretation of raw data.

OR (b) exclude hypothesis A (universal validity of QM).

Objections:

(1) Macrovariable $\Rightarrow S \gg h \Rightarrow$ predictions of QM indistinguishable from those of CM.

Solution: Find macrovariable whose motion is controlled by microenergy.

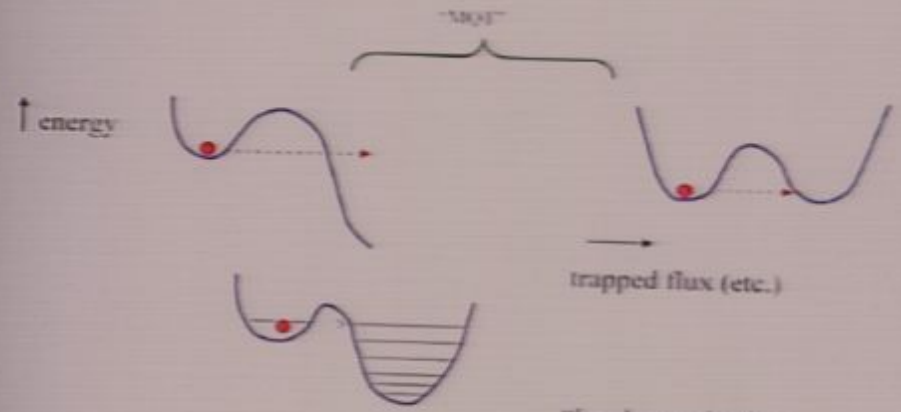
(2) Decoherence $\Rightarrow$ stage 2 impossible in practice.
Solution: Find system with very small dissipation.

(3) Hamiltonian of macrosystem unknown in detail $\Rightarrow$ can never make QM'I predictions with sufficient confidence to draw conclusion (3b).

Stage 1. Circumstantial tests of applicability of QM to macroscopic variables.

(mostly Josephson junctions and SQUIDS)

e.g.

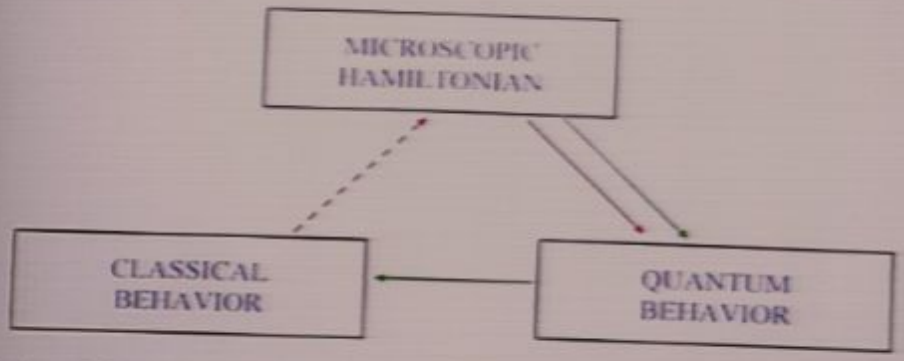


"level quantization/
Resonant tunnelling"

Tests conjunction of (a) applicability of QM to macrovariables

(b) treatment of dissipation

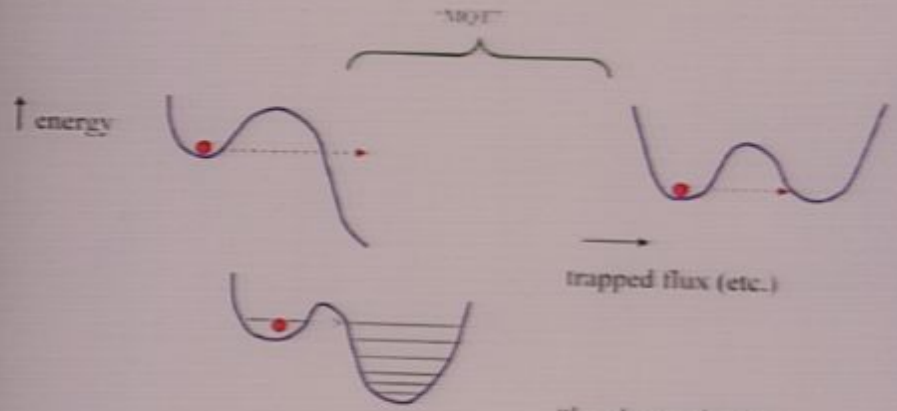
Not direct evidence of QIMDS.



Stage 1. Circumstantial tests of applicability of QM to macroscopic variables.

(mostly Josephson junctions and SQUIDS)

e.g.



Tests conjunction of (a) applicability of QM to macrovariables

(b) treatment of dissipation

Not direct evidence of QIMDS.

How to Infer Quantum Behavior from Classical?

$$\hat{H} = \hat{H}_S + \hat{H}_E + \hat{H}_{S-E}$$

If any **one** degree of freedom of env^t only "weakly" perturbed, then can model $\hat{H}_E$ and $\hat{H}_{S-E}$ as follows*:

$$\hat{H}_E = \hat{H}_{SHO} \equiv \sum_\alpha \left\{ \tfrac{1}{2} m_\alpha \omega_\alpha^2 x_\alpha^2 + \tfrac{1}{2} p_\alpha^2 / m_\alpha^2 \right\}$$

$$\hat{H}_{S-E} = \sum_\alpha f_\alpha(q) x_\alpha$$

In many cases of practical interest, can argue from general "microscopic" knowledge that

$$f_\alpha(q) = q C_\alpha \quad (+ \text{counterterm})$$

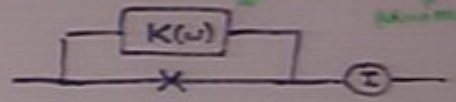
Then def.

$$J(\omega) \equiv \sum_\alpha (C_\alpha^2 / m_\alpha \omega_\alpha) \delta(\omega - \omega_\alpha)$$

"spectral density of S-E coupling"

$J(\omega)$ uniquely determines **both classical and quantum response!** (AJL, Phys. Rev. B **30**, 1208 (1984))

Ex.: current-biased Josephson junction:



det. $K(\omega)$ from behavior in classical limit, set $J(\omega) = \mathrm{Im}\, K(\omega)$, input into (e.g.) calc^n of quantum tunneling out of zero-voltage state.

* A.O. Caldeira and A.J.L., Ann. Phys. **149**, 374 (1983), appendix C

How to Infer Quantum Behavior from Classical?

$$\hat{H} = \hat{H}_S + \hat{H}_E + \hat{H}_{S-E}$$

system   env^t system–env^t interaction

If any **one** degree of freedom of env^t only "weakly" perturbed, then can model $\hat{H}_E$ and $\hat{H}_{S-E}$ as follows*:

$$\hat{H}_E = \hat{H}_{SHO} \equiv \sum_\alpha \left\{ \tfrac{1}{2} m_\alpha \omega_\alpha^2 x_\alpha^2 + \tfrac{1}{2} p_\alpha^2 / m_\alpha \right\}$$

$$\hat{H}_{S-E} = \sum_\alpha f_\alpha(q) x_\alpha$$

sys… … cond…

In many cases of prac… interest, can argue from general "microscopic" … that

$$f_\alpha(q … C_\alpha \quad (+\text{counterterm})$$

Then df.

$$J(… \omega_\alpha)\, \delta(\omega - \omega_\alpha)$$

… S–E coupling"

$J(\omega)$ … classical and quantum response … 1984))

Ex…

J…

…sical limit, set

J… calc^n of quantum

…

… Phys. 149, 374 (1983), appendix C

How to Infer Quantum Behavior from Classical?

$$\hat{H} = \hat{H}_S + \hat{H}_E + \hat{H}_{S-E}$$

If any one degree of freedom of env^t only "weakly" perturbed, then can model $\hat{H}_E$ and $\hat{H}_{S-E}$ as follows*:

$$\hat{H}_E = \hat{H}_{SHO} \equiv \sum_\alpha \left\{ \tfrac{1}{2} m_\alpha \omega_\alpha^2 x_\alpha^2 + \tfrac{1}{2} p_\alpha^2 / m_\alpha^2 \right\}$$

$$\hat{H}_{S-E} = \sum_\alpha f_\alpha(q_S)\, x_\alpha$$

In many cases of practical interest, can argue from general "microscopic" knowledge that

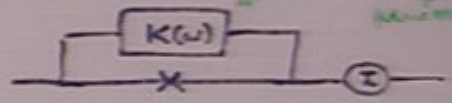
$$f_\alpha(q_S) = q_S C_\alpha \quad (+\text{counterterm})$$

Then def.

$$J(\omega) \equiv \sum_\alpha (C_\alpha^2 / m_\alpha \omega_\alpha)\, \delta(\omega - \omega_\alpha)$$

$J(\omega)$ uniquely determines both classical and quantum response! (AJL, Phys. Rev. B 30, 1208 (1984))

Ex.: current-biased Josephson junction:



det. $K(\omega)$ from behavior in classical limit, set $J(\omega) = \mathrm{Im}\, K(\omega)$, input into (e.g.) calc^n of quantum tunneling out of zero-voltage state.

* A.O. Caldeira and A.J.L., Ann. Phys. 149, 374 (1983), appendix C

$$\hat{H} = \hat{H}_s + \hat{H}_E + \hat{H}_{s-E}$$

system — env^t — system–env^t interaction

If any **one** degree of freedom of env^t only "weakly" perturbed, then can model $\hat{H}_E$ and $\hat{H}_{s-E}$ as follows*:

$$\hat{H}_E = \hat{H}_{osc} \equiv \sum_\alpha \left\{ \tfrac{1}{2} m_\alpha \omega_\alpha^2 x_\alpha^2 + \tfrac{1}{2} p_\alpha^2 / m_\alpha^2 \right\}$$

$$\hat{H}_{s-E} = \sum_\alpha f_\alpha(q)\, x_\alpha$$

system coord.

In many cases of practical interest, can argue from general "microscopic" knowledge that

$$f_\alpha(q) = q C_\alpha \quad (+ \text{counterterm})$$

Then def.

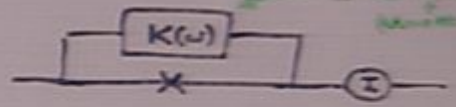
$$J(\omega) \equiv \sum_\alpha (C_\alpha^2 / m_\alpha \omega_\alpha)\, \delta(\omega - \omega_\alpha)$$

"spectral density of S-E coupling"

$J(\omega)$ uniquely determines **both classical and quantum response!** (AJL, Phys. Rev. B **30**, 1208 (1984))

$\Xi \omega Y(\omega)$ (dissipation)

Ex.: current-biased Josephson junction:



det. $K(\omega)$ from behavior in classical limit, set $J(\omega) = \mathrm{Im}\, K(\omega)$, input into (e.g.) calc^n of quantum tunneling out of zero-voltage state.

* A.O. Caldeira and A.J.L., Ann. Phys. **149**, 374 (1983), appendix C